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Verification and Aerodynamic Calibration of the Tunnel 16T Captive Trajectory Support (CTS) System

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Calspan Corporation**

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Verification and Aerodynamic Calibration of the Tunnel 16T Captive Trajectory
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PREFACE

The work reported herein was conducted at the Arnold Engineering Development Center, (AEDC), Air Force Systems Command, (AFSC), at the request of the AEDC Directorate of Aerospace Flight Dynamics Test (AEDC/DOF). The test results were obtained by Calspan Corporation/AEDC Division, operating contractor for the aerospace flight dynamics test facilities at AEDC, AFSC, Arnold Air Force Station, Tennessee. The AEDC/DO project manager was Capt. J. K. Gibby, and the Calspan project engineer was Mr. E. G. Allee. The test was conducted in the Propulsion Wind Tunnel Facility (PWT), in the Propulsion Wind Tunnel (16T), during the period from July 21, 1985 through July 26, 1985 under AEDC Project Number CC83PG, PWT Test Number TF694. The manuscript was submitted for publication on December 20, 1985.

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1.0 INTRODUCTION

The Captive Trajectory Support (CTS) system is used primarily for the trajectory analysis of air-launched stores from aircraft. It is part of a motion simulator which uses the wind tunnel as a six-degree-of-freedom function generator for the aerodynamic coefficients of the store. The CTS system is also used for obtaining aerodynamic coefficient data at predetermined spatial points (grid) in an aircraft flow field. Captive trajectory and grid testing have been conducted since 1968 in Tunnel 4T of the Propulsion Wind Tunnel (PWT) facility at AEDC. However, the relatively small size of this wind tunnel limits the aircraft angle of attack to approximately 20 deg and the model size to a small scale (approximately 5 percent). During August 1985, a Tunnel 16T CTS system operational capability was demonstrated. The test capability in Tunnel 16T will provide:

1. A better geometric reproduction of the stores and aircraft/store interfaces (pylons and racks) by using up to 25-percent scale models,
2. Enhanced capability to simulate fin and control surface deployment during separation, with automated control surface deflections after deployment,
3. Ability to investigate missile separation up to an aircraft angle of attack of 45 deg, and
4. Ability to simulate rocket exhaust plumes (using cold air jets) during missile launches.

The purpose of this report is to document the results of the CTS system demonstration test conducted in Tunnel 16T. The test objectives were to: (1) demonstrate the structural integrity of the Captive Trajectory Support (CTS) system throughout the operating envelope of Tunnel 16T; (2) demonstrate the ability of the CTS system to satisfactorily obtain grid and trajectory generation data for a typical store model in a dynamic wind tunnel environment; and (3) obtain a test section Mach number calibration for the Tunnel 16T Cart 2 (Multi-Purpose Cart) with the CTS system installed. Only typical results from the test section calibration and the CTS system operational verifications are included in this report.

2.0 APPARATUS

2.1 TEST FACILITY

2.1.1 General

The AEDC Propulsion Wind Tunnel (16T) is a variable density, continuous-flow tunnel capable of being operated at Mach numbers from 0.06 to 1.60 and stagnation pressures from 120 to 4000 psfa. The maximum attainable Mach number can vary slightly depending upon the tunnel pressure ratio requirements with a particular test installation. The maximum stagnation pressure attainable is a function of Mach number. The tunnel stagnation temperature can be varied from about 80 to 160°F depending upon the cooling water temperature. The tunnel is equipped with a scavenging system which removes combustion products when testing rocket motors or turbo-engines.

2.1.2 Test Cart

The test section used during this test was the Tunnel 16T Multi-Purpose Cart configured for CTS testing and designated Cart 2C. The Cart 2C is 16 ft square by 40 ft long and enclosed by 60-deg inclined-hole perforated walls of six-percent porosity. Although the Cart 2C test section has a side wall angle variation capability from 1.5-deg convergence to 1.0-deg divergence, the test included only wall angles of 0.0-deg and 0.5-deg divergence. To compensate for the tunnel blockage caused by the CTS strut and boom, the Cart 2C sidewalls have a bulge section that increased the test section width (in the strut area) 14.6 in. A photograph of the general arrangement of Cart 2C with the CTS/test article hardware for the verification phase installed is shown in Fig. 1. Additional information about the tunnel, its capabilities, and the operating characteristics is presented in Ref. 1.

2.2 CAPTIVE TRAJECTORY SUPPORT SYSTEM

Aerodynamic loads and captive trajectory testing were conducted using the CTS to support the store model. The GAM II strut was installed on the electrically driven pitch table to support a flat plate with pylons to simulate an aircraft model. A block diagram of the computer network used to control the CTS system and an isometric drawing of a typical CTS installation in Tunnel 16T are given in Figs. 2 and 3, respectively. For additional information concerning the CTS system, see Reference 2.

2.3 TEST ARTICLES

The test articles were a 1/4-scale Maximum Volume Bomb (MVB) store model and a flat plate which simulated an aircraft model. The details of the store model showing its primary dimensions and component parts are presented in Fig. 4. The MVB was sting-mounted on

the Tunnel 16T CTS system using a variable offset roll mechanism adjusted for a 10-in. offset. The flat plate had two "boiler plate" pylons. One pylon was set at a yaw angle of 0 deg, and the second pylon was yawed at 10 deg outboard. The flat plate was mounted on the Propulsion Wind Tunnel (PWT) GAM II strut. The general arrangement of the simulated aircraft model, showing its primary dimensions and component parts, is presented in Fig. 5.

2.4 INSTRUMENTATION

2.4.1 Operational Verification Phase

A six-component internal strain-gage balance was used to measure the aerodynamic forces and moments on the MVB. Translational and angular positions of the store were obtained from the CTS analog outputs. The flat plate angle of attack was measured by a Shaevitz® angular position indicator mounted on the underside of the plate. Two infrared optical touch sensors were placed in each pylon on the flat plate which enabled the MVB to be positioned accurately for initiating trajectories. The CTS system was electrically wired to automatically stop the CTS movement if the store, its sting support, or the CTS rig contacted any surface in the tunnel.

2.4.2 Calibration Phase

A total of 122 static pressures were measured using individual Setra® transducers connected to orifices in the tunnel walls. Seventeen orifices were located on the tunnel floor centerline of the nozzle transition section, and 105 orifices were located on the floor and ceiling of the test section.

3.0 TEST DESCRIPTION

3.1 TEST CONDITIONS

3.1.1 Verification Phase

Grid and trajectory data were obtained for Mach numbers from 0.7 to 1.1 and at Reynolds numbers to match Tunnel 4T test conditions. A matrix listing test conditions is presented in Table 1 for the grid and trajectory runs. A description of each configuration, identified by a configuration number, is listed in Table 2.

3.1.2 Calibration Phase

Calibration data were obtained at Mach numbers from 0.3 to 1.6, stagnation pressures of 400, 550, 1200, and 1600 psfa, wall angles of 0.0 and 0.5 deg diverged, and various tunnel pressure ratios. A matrix of the test conditions is presented in Table 3.

3.2 DATA ACQUISITION AND REDUCTION

3.2.1 Verification Phase

3.2.1.1 Captive Trajectory Data

To obtain a trajectory, test conditions were first established in the tunnel. Data from the tunnel, consisting of measured store model forces and moments, and wind tunnel operating conditions were input to the Digital Data Acquisition System (DDAS) computer for use in the full-scale trajectory calculations. In order to calculate the full-scale store trajectories, the measured wind tunnel force and moment data were reduced to coefficient form and then adjusted with proper full-scale store dimensions and flight dynamic pressure to obtain full-scale loads. The dynamic pressure was calculated using a flight velocity equal to the full-scale aircraft simulated velocity plus the components of store velocity relative to the aircraft and a density corresponding to the simulated altitude.

3.2.1.2 Grid data

Free-stream grid aerodynamic coefficient data were acquired during the test. To obtain store grid data, test conditions were first established in the tunnel. Operational control of the store model support systems was then switched to the digital computer which positioned the store at selected angles of attack through commands to the CTS system (see block diagram, Fig. 2).

3.2.1.3 Calibration Phase

Calibration data were obtained with the CTS boom positioned fully aft, mid-travel, and fully forward on the tunnel centerline. Data were also obtained with the strut positioned 4.5 ft east of the tunnel centerline and the boom positioned 4.3 ft above the tunnel centerline to assess the effects of the CTS boom and strut location on the tunnel calibration.

The local Mach number distributions in the test section were obtained from the wall static pressure data and the stilling chamber total pressure. Isentropic flow through the tunnel nozzle was assumed. The average Mach number and an estimate of two times the standard deviation of the axial Mach number distribution were computed during the calibration phase to permit an on-line evaluation of the relative Mach number distribution quality. The estimate of the axial Mach number deviation was computed as:

$$2\sigma = 2 \left\{ \left[\frac{\sum_{i=1}^n (M_i - M_a)^2}{n - 1} \right] \right\}^{1/2} \quad (1)$$

When applied to Mach number axial distributions, the 2σ Mach number deviation is a measure of the relative quality of the distribution. The minimum Mach number deviation for a particular test section length and set of tunnel conditions is indicative of the smoothest distribution.

The calibration of Tunnel 16T is based on the measured pressure differential between the test section and the plenum chamber at various operating conditions. The test section Mach number (M_a) was defined as the average Mach number determined from the solid floor plate orifices. An equivalent plenum chamber Mach number (M_c) was calculated from plenum chamber and tunnel stagnation pressure measurements using the isentropic relationship. A calibration parameter, defined as the difference between the test section and equivalent plenum chamber Mach numbers ($M_a - M_c$), is used to express the tunnel calibration for various operating conditions.

3.3 CORRECTIONS

Balance, sting, and support linear and angular deflections, caused by the aerodynamic loads on the store model during the captive trajectory and free-stream grid testing, were included as corrections in the data reduction program to calculate the true store-model angles and positions. Corrections were also made for model weight tares in calculating the net aerodynamic forces on the store model.

3.4 UNCERTAINTIES/PRECISION OF MEASUREMENTS

A Taylor series method of error propagation (Ref. 3) was used to estimate the uncertainty of the data which could be attributed to instrumentation errors and data acquisition techniques. Uncertainties (combinations of systematic and random errors) of the basic tunnel parameters were estimated from repeat calibrations of the instrumentation and from the repeatability and uniformity of the test section flow during tunnel calibration. Uncertainties in the instrumentation systems were estimated from repeat calibrations of the systems against secondary standards whose uncertainties are traceable to the National Bureau of Standards calibration equipment.

The uncertainties in store positioning, based on the ability of the CTS to set a specific value, were measured to be ± 0.10 in. in axial, horizontal, and vertical position, ± 0.10 deg in pitch and yaw, and ± 0.5 deg in roll. The estimated uncertainty in the simulated aircraft model angle of attack was ± 0.1 deg.

The major sources of errors in trajectory data are tunnel conditions, balance measurements, and CTS positioning control. The estimated uncertainties in the full-scale position data of the MVB store are given in Table 4.

For the grid data, the balance uncertainties, based on a 95-percent confidence level, were combined with the uncertainties in the tunnel parameters using a Taylor series method of error propagation (Ref. 3) to estimate the uncertainties of the store aerodynamic coefficients. These uncertainties are given in Table 5.

The uncertainties in the calibration parameters are presented in Table 6.

4.0 RESULTS AND DISCUSSION

Selected tunnel calibration, aerodynamic free-stream data, and trajectory data acquired both in the free stream and from the pylons of a simulated (flat-plate) aircraft are presented in this section. The free-stream data are presented in Fig. 6, the trajectory data in Figs. 7 through 10, and the calibration data in Figs. 11 through 22.

4.1 OPERATIONAL VERIFICATION

For the operational verification phase of the test, the objective was to ensure that the 16T CTS system would exhibit acceptable operational characteristics and provide adequate aerodynamic grid free-stream and trajectory data quality under actual test conditions. The aerodynamic coefficient data were compared with data from the same store taken on a previous test in the Aerodynamic Wind Tunnel (4T). The Tunnel 4T data are presented for an angle-of-attack range of -6 to 22 deg and zero sideslip angle. An example of these data is shown in Fig. 6. The differences between the data are on the same order of magnitude as the uncertainties presented in Table 5 and are considered good agreement.

The CTS system has the capability to operate in both a move-pause mode, in which the store motion is halted at each position at which data are required, and in the continuous-motion (velocity-control) mode, in which data are acquired without stopping the store as it moves through the desired positions. A description of the two modes is included in Ref. 4. In both modes, the data are acquired from the Digital Data Acquisition System (DDAS). The DDAS is used to acquire, filter, and preprocess force and moment and CTS position data from the store strain-gage balances and the six CTS position potentiometers. These analog data are amplified, filtered with analog prefilters, digitized, and then digitally filtered with a second-order autoregression technique that maintains a continuous average of input data. The preprocessing time required for extensive digital filtering may produce large CTS position errors in the velocity-control mode. Therefore, a digital filter cutoff frequency constant and

a sample rate are preselected for use in the computer that will minimize position errors and yet provide quality aerodynamic force and moment data. The constant which is input to the DDAS is determined by comparing data acquired with various frequency cutoff constants while the system is operating in the velocity-control mode with those aerodynamic coefficients obtained with the system in the move-pause mode. A comparison of these data with no digital filtering, digital filtering with cutoff frequencies of 1.0 and 1.5 Hz, a DDAS sample rate of 50 Hz, and an analog frequency cutoff of 4 Hz is given in Fig. 7. Since the aerodynamic force and moment data differences were within the balance uncertainties both with and without digital filtering, it appears that for this particular model/strain-gage balance installation that the analog filter provided adequate filtering.

To verify operation of the CTS system computer software, the following approach was used:

1. An off-line trajectory was generated using the AEDC Trajectory Generation Program (TGP). An initial force and moment value was used with all aerodynamic forces set to zero. The same initial conditions were then input to the operational 16T CTS program, which operated in a simulate mode. When the system is in simulate mode, all aspects of the hardware and software, except for actual rig movement, are exercised. The resulting data are presented in Fig. 8. No differences in the trajectories calculated by the two programs were noted.
2. Free-stream aerodynamic coefficient data obtained on the MVB in Tunnel 16T were input into the off-line TGP along with initial ejection forces, and a simulated trajectory was calculated. The calculated trajectory was compared with one obtained on-line in Tunnel 16T which had the same initial conditions. These trajectories are shown in Fig. 9. No difference is discernible in the vertical and axial positions between the two trajectories. The small difference in pitch angle during the second pitch cycle was due to the interpolation routine used by the off-line TGP in determining the aerodynamic coefficient input.
3. The digital filtering constant selected for use during the aerodynamic grid program was validated for the trajectory program by obtaining a trajectory in the move-pause mode and then repeating it with the system in the velocity-control mode. As shown in Fig. 10, no differences in the data were evident.
4. The final phase of the operational verification demonstrated the ability of the CTS system to position a store in close proximity to an aircraft. The system was commanded to move the store to within 0.2 in. of a pylon mounted on a flat plate. After the store was set to the desired position, a trajectory was

automatically initiated. This phase demonstrated the CTS can “dock” a store to an aircraft which is at various angles of attack and/or sideslip angle within the required positional tolerances for store separation testing.

Based on the data obtained during the operational verification phase, the Captive Trajectory Support System can obtain aerodynamic coefficient grid and captive trajectory data in both move-pause and velocity-control modes of operation, over its full range of angular and linear travel capabilities.

4.2 MACH NUMBER CALIBRATION

4.2.1 General

The Mach number calibration was verified during the calibration phase by measuring the pressure distribution on the floor of the test section using orifices installed in 2-ft-wide solid wall plates. The results of the data from the solid wall plates were compared to data obtained during a previous calibration of Cart 2 (Ref. 5) to determine if the Mach number calibration should be changed for CTS testing. The criterion used to judge the validity of the previous calibration for CTS testing was based on an acceptable Mach number tolerance for CTS testing of ± 0.005 . Data obtained during the calibration reported in Ref. 5 indicated an average Mach number difference between the centerline and solid floor plate measurements of less than 0.001 for subsonic Mach numbers and 0.002 at supersonic Mach numbers. The small differences between the centerline and floor solid plate data made it possible to use only the floor measurements to check the Mach number calibration of the CTS test section.

To verify the calibration of the CTS test section, a calibration region was selected that varied with the CTS boom axial position. The calibration region is defined as the region from tunnel station 1 to the tunnel station where CTS aerodynamic interference becomes significant, which was 5.4 ft upstream of the CTS pitch center. The 5.4-ft distance that significant aerodynamic interference propagates upstream of the CTS was determined from investigations conducted in Tunnels 4T and 1T. A schematic of the calibration region is shown in Fig. 11.

4.2.2 Wall Angle Selection

Calibration data were obtained at $\theta = 0.0$ and 0.5 deg during the calibration phase. Data were obtained at these two test section wall angles to ensure that the trends relative to flow quality observed during a Tunnel 1T investigation of the CTS were repeated in Tunnel 16T. The Tunnel 1T investigation of the CTS indicated that the 2σ Mach number deviations were minimized at $\theta = 0.5$ deg. The 2σ Mach number deviations obtained in Tunnel 16T at $\theta = 0.0$ and 0.5 deg are shown in Fig. 12. Although the 2σ Mach number deviations for

the two wall angles differ only slightly, the distributions at $\theta = 0.5$ deg are the same or better at each Mach number.

Diverging the test section wall 0.5 deg will increase the test section area which reduces the CTS blockage, thus reducing power requirements. Data obtained at $M = 1.20$ and $P_T = 1200$ psfa show that an 11-percent reduction in total power was obtained by diverging the test section walls 0.5 deg.

Based on achieving smoother Mach number distributions and lower power requirements for $\theta = 0.5$ deg compared to 0.0 deg, the recommended test section wall angle for CTS testing is $\theta = 0.5$ deg. The remainder of the calibration data presented herein were obtained at $\theta = 0.5$ deg.

4.2.3 Tunnel Pressure Ratio Effects

Tunnel pressure ratio was varied during the calibration phase to determine the minimum pressure ratio operating schedule for CTS testing. The minimum operating tunnel pressure ratio schedule is defined as the minimum tunnel pressure ratio at each Mach number that provides Mach number variation through the calibration region of less than 0.005 when the test section is empty. The typical effect of tunnel pressure ratio variation on the Mach number distributions is shown in Fig. 13. The 2σ Mach number deviations in the calibration region at various Mach numbers with varying tunnel pressure ratio are shown in Fig. 14. The tunnel pressure ratio variation shown in Fig. 14 is typical of most tests that will be run in Tunnel 16T. The data show that varying the tunnel pressure ratio over a typical operating range will not affect the Mach number distribution in the calibration region.

The effect of varying tunnel pressure ratio on the calibration is shown in Fig. 15. The results, which are typical of previous calibrations, show that the calibration is not a function of tunnel pressure ratio within a typical variation range. For $M < 0.75$, tunnel pressure ratio is not a calibration variable because plenum suction is not used, and only the pressure ratio sets Mach number.

The nominal operating tunnel pressure ratios, λ^* , that are recommended for CTS testing are defined in Fig. 15. Although no significant effect of tunnel pressure ratio variation on the Mach number distribution in the calibration region was observed, conservative nominal tunnel pressure ratios are recommended until better criteria are established based on CTS testing experience. Normal tunnel operations with models installed in the test section require tunnel pressure ratios that are higher than the minimum tunnel pressure ratio required for acceptable Mach number distributions with the test section empty. The nominal tunnel pressure ratio and corresponding compressor pressure ratio schedules are presented in Table 7.

4.2.4 CTS Position Effects

4.2.4.1 Boom Axial Position

The effect of axial variation of the CTS boom position on the Mach number distributions is shown in Fig. 16. As the boom axially traverses the test section, CTS interference causes the Mach number in the calibration region to vary less than the 0.005 Mach number tolerance which is acceptable for CTS testing.

The effect of boom axial position on the tunnel calibration is shown in Fig. 17. The largest variation of the calibration parameter with axial boom movement is 0.003 and occurs at $M = 1.20$ with the boom in the full-forward position. The forward boom position will rarely be required during testing, and the variation is negligible for CTS testing. Therefore, it is concluded that the calibration of the CTS test section as a function of boom axial position is not required. The previous calibration values (Ref. 5), for Cart 2, are indicated in Fig. 17 for comparison. The largest variation of the calibration parameter from the previous calibration is 0.004 in Mach number which also occurs at $M = 1.20$ with the boom fully forward. In general, when the boom is at mid-travel or farther downstream, the calibration parameter agrees within 0.002 of the previous calibration of Cart 2.

4.2.4.2 Vertical and Horizontal CTS Position

Typical effects of the CTS boom vertical position and the CTS strut horizontal position on the Mach number distributions are shown in Fig. 18. The effect of the CTS off-centerline movements on the 2σ Mach number deviations is shown in Fig. 19. The vertical and horizontal movement of the CTS had a negligible effect on the Mach number distributions.

The effect of CTS boom vertical position and CTS strut horizontal position on the tunnel calibration is shown in Fig. 20. The calibration varies less than 0.001 for the data that were obtained. Thus, these data indicate that vertical and horizontal movement of the CTS has no significant effect on the calibration.

4.2.5 Reynolds Number Effects

The Reynolds number was varied over the full range of the CTS capability during the calibration phase. Typical Mach number distributions at various Reynolds numbers are shown in Fig. 21. Reynolds number variation has no significant effect on the Mach number distributions.

The effect of Reynolds number variation on the calibration parameter is shown in Fig. 22. The calibration parameter varied less than 0.002 with Reynolds number variation which is within the acceptable tolerance of ± 0.005 . Therefore, for CTS testing the Mach number calibration does not vary significantly within the Reynolds number range available.

The calibration values from the previous calibration (Ref. 5) are indicated in Fig. 22. The largest difference between the CTS calibration parameter and the previous calibration parameter is 0.004 which occurs at $M = 1.60$, $P_T = 1200$ psfa. For subsonic Mach numbers, the CTS calibration is within 0.001 in Mach number of the previous calibration.

4.2.6 Recommended Calibration for CTS Testing

The previous Cart 2 calibration (Ref. 5) is considered adequate for CTS testing based on the data presented in Figs. 17 and 22. The largest differences between the data obtained during the CTS calibration and the previous calibration occur at supersonic Mach numbers or with the CTS boom extended to the full-forward position. The differences between the calibration data were always less than 0.005 in Mach number and usually less than 0.002. Therefore, the previous calibration (Ref. 5) will be used for CTS testing.

5.0 CONCLUSIONS

Conclusions reached as a result of the 16T Captive Trajectory System Air-on Demonstration test are as follows:

1. The Captive Trajectory Support system can obtain aerodynamic coefficient grid and captive trajectory data in both move-pause and velocity-control modes of operation over its full range of angular and linear travel capabilities.
2. The system can "dock" a store with an aircraft which is at various angles of attack and/or sideslip within the required positional tolerances for store separation testing.
3. Quality of the aerodynamic force and moment data acquired with the 16T Captive Trajectory Support system is comparable to that obtained in Tunnel 4T.
4. The calibration of the Captive Trajectory Support test section does not vary significantly with tunnel pressure ratio, CTS position, or tunnel unit Reynolds number.

5. Based on smooth Mach number distribution and lower power requirements, the test section wall angle recommended for Captive Trajectory Support testing in Tunnel 16T is 0.5 deg diverged.
6. The previous test section calibration for Cart 2, without the Captive Trajectory Support capability, adequately defines test conditions and will be used for Captive Trajectory Support testing.

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1. *Test Facility Handbook* (Twelfth Edition). "Propulsion Wind Tunnel Facility, Vol. 4." Arnold Engineering Development Center, March 1985.
2. Carman, Jack B., Hill, D. W., and Christopher, J. P. "Store Separation Testing Techniques at the Arnold Engineering Development Center, Vol. II: Description of Captive Trajectory Store Separation Testing in the Aerodynamic Wind Tunnel (4T)" AEDC-TR-79-1 (AD-AO87561), June 1980.
3. Abernethy, R. B., and Thompson, J. W., et al. "Handbook-Uncertainty in Gas Turbine Measurements." AEDC-TR-73-5 (AD-755356), February 1973.
4. Hill, D. W., Jr. "Development of a Velocity Control Algorithm for Controlling a 6 DOF Captive Trajectory Model Support" *Proceedings of the 29th International Symposium, Instrument Society of America*, Albuquerque, New Mexico, May 1983, pp. 353-367.
5. Jackson, F. M. "Calibration of the AEDC-PWT 16-FT Transonic Tunnel Aerodynamic Test Section at Various Reynolds Numbers." AEDC-TR-78-60 (AD-AO65112), February 1979.

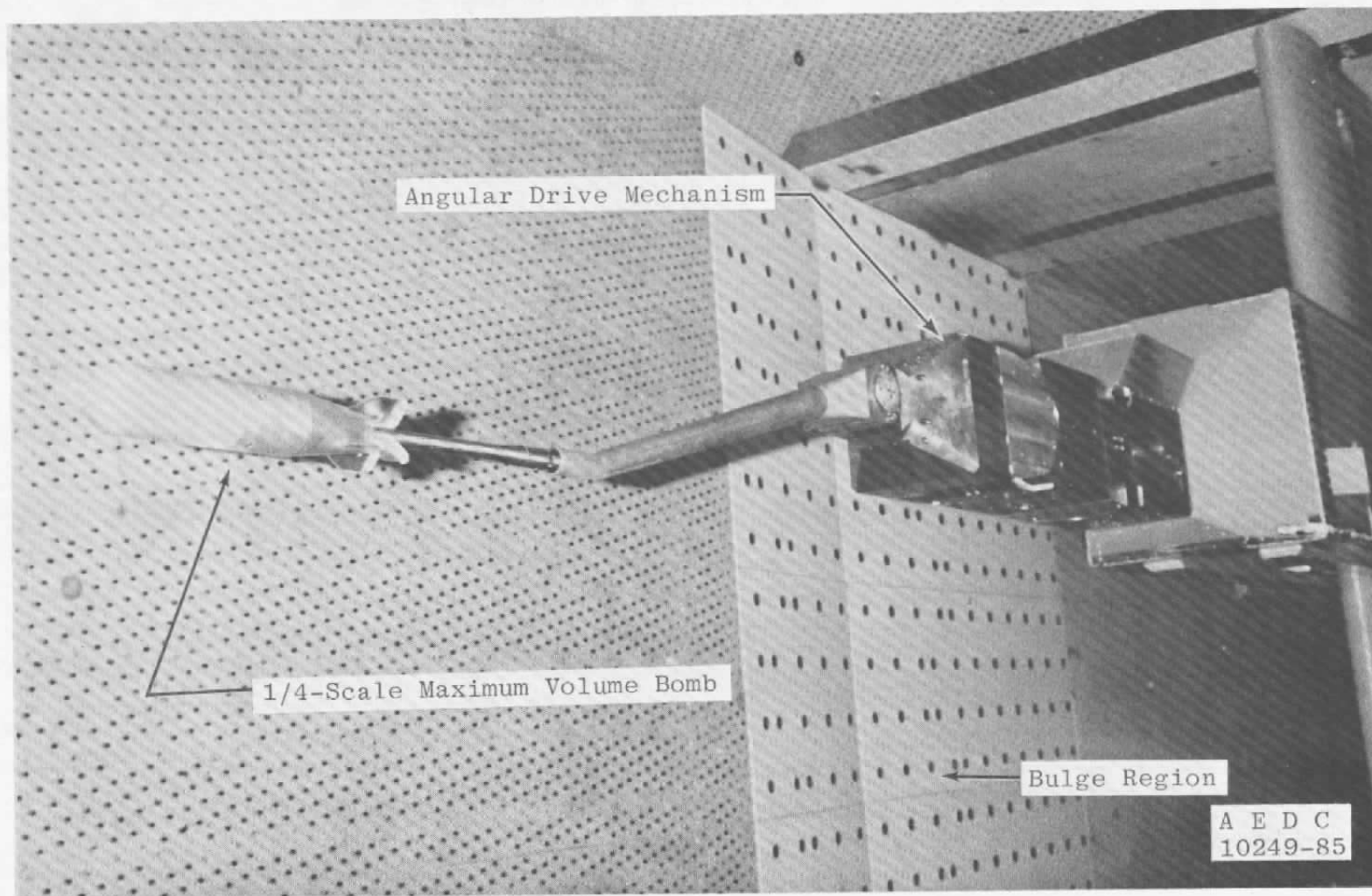


Figure 1. Test article installation in Tunnel 16T.

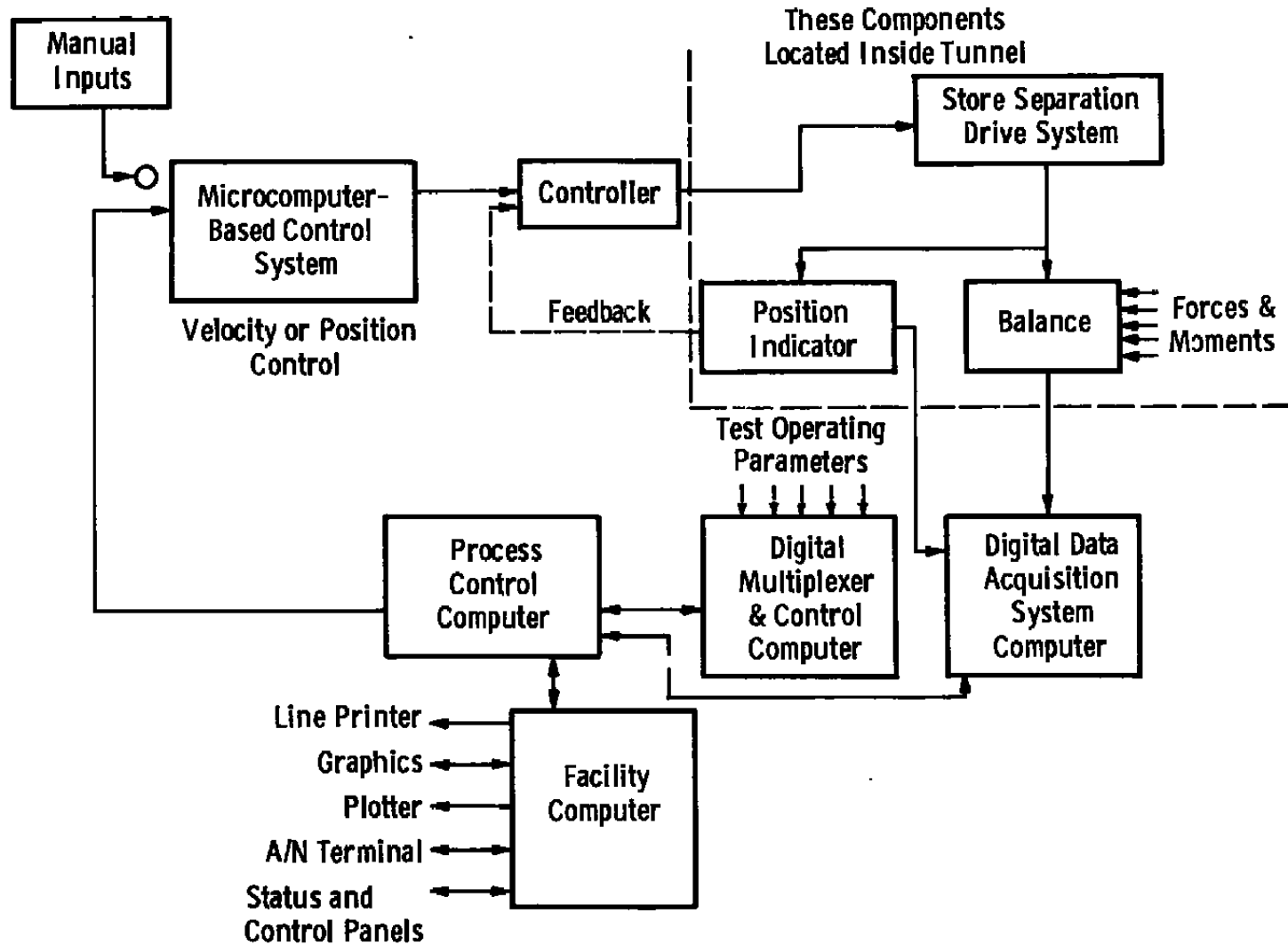


Figure 2. Block diagram of the computer network for CTS control.

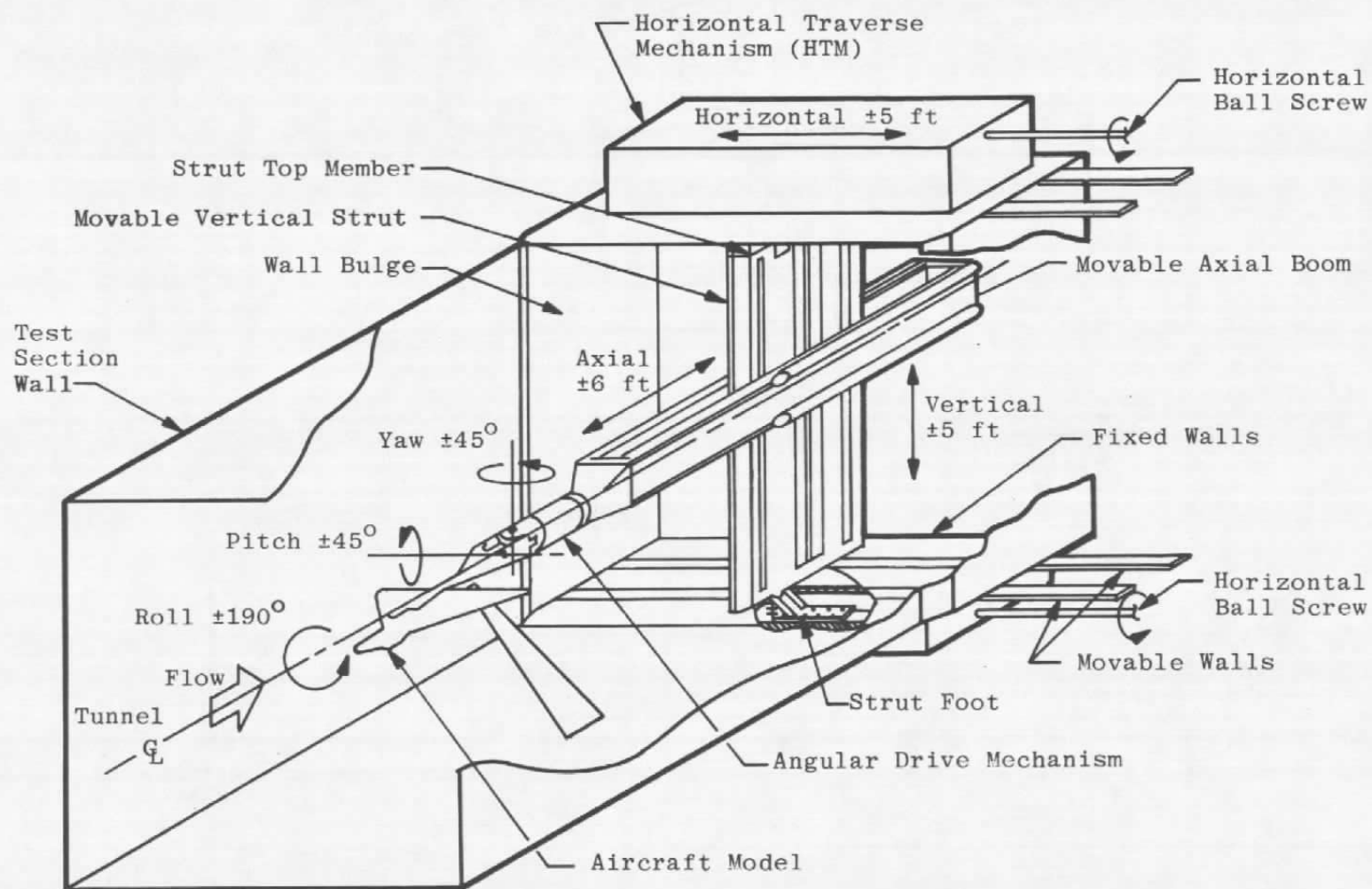


Figure 3. Tunnel 16T CTS installation and design travel limits.

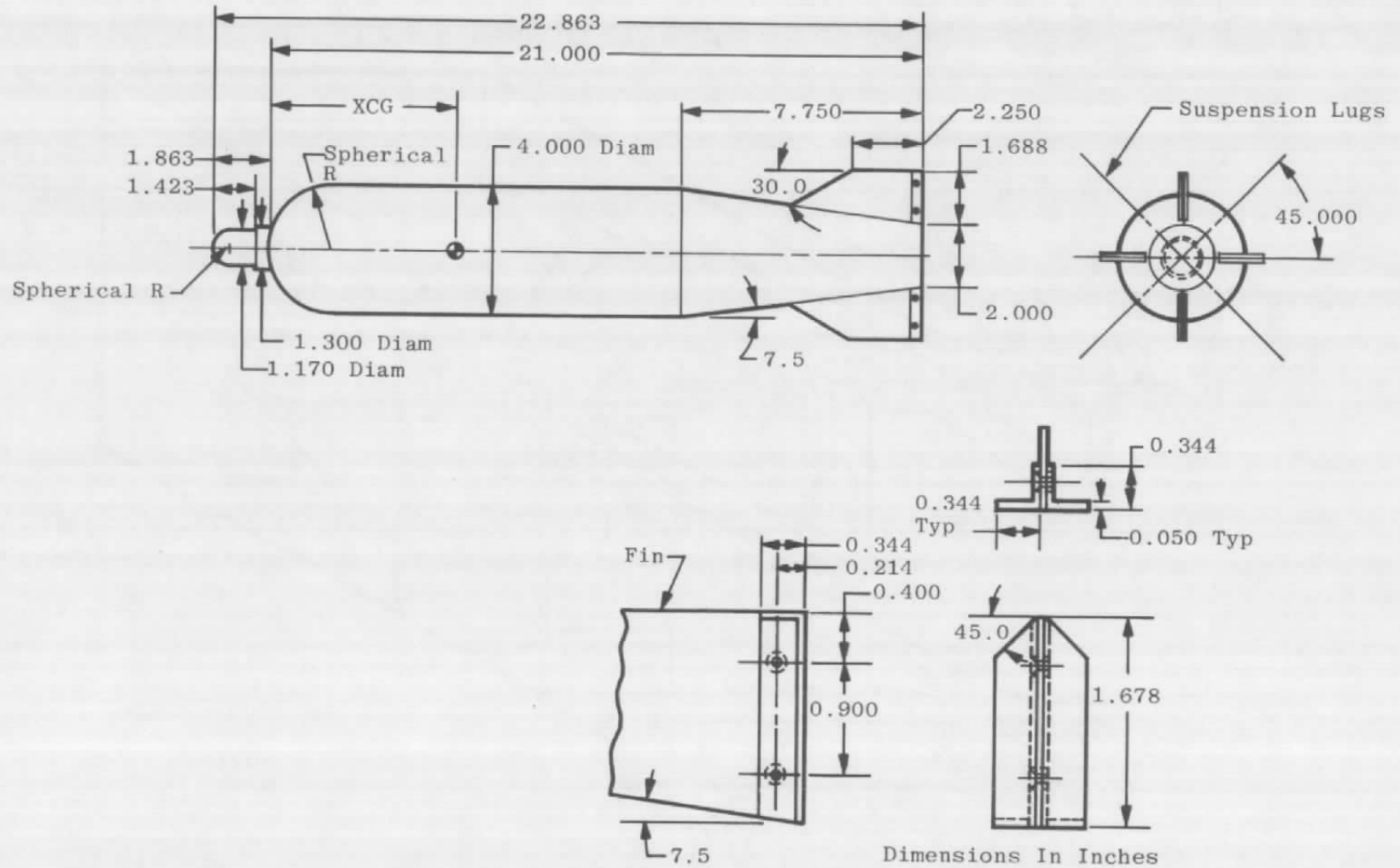


Figure 4. Details and dimensions of the 0.25-Scale MVB model.

***16T Air-On Demo (Grid) ***
 Run = 15,954,955
 1 4T Free-Stream Aerodynamic Coefficients
 2,3 16T Free-Stream Aerodynamic Coefficients

Mach = 0.9

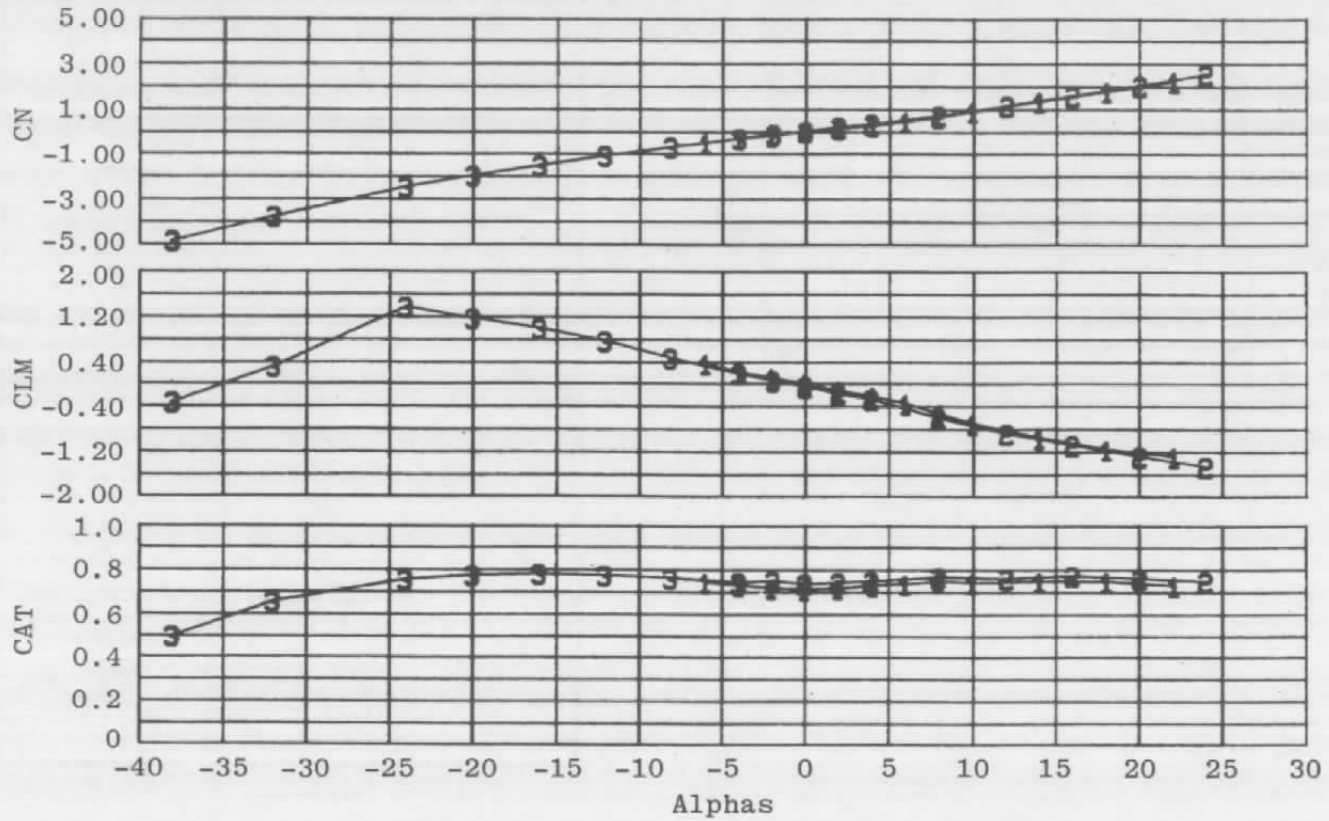


Figure 6. Comparison of 4T and 16T aerodynamic coefficients.

*** 16T Air-On Demo (Grid) ***
 Run = 954, 955, 972, 973, 960, 961, 974, 975
 1,2 Move-Pause
 3,4 No Digital Filtering
 5,6 Digital Filter Cutoff Frequency = 1.0 Hz
 7,8 Digital Filter Cutoff Frequency = 1.5 Hz

Mach = 0.9

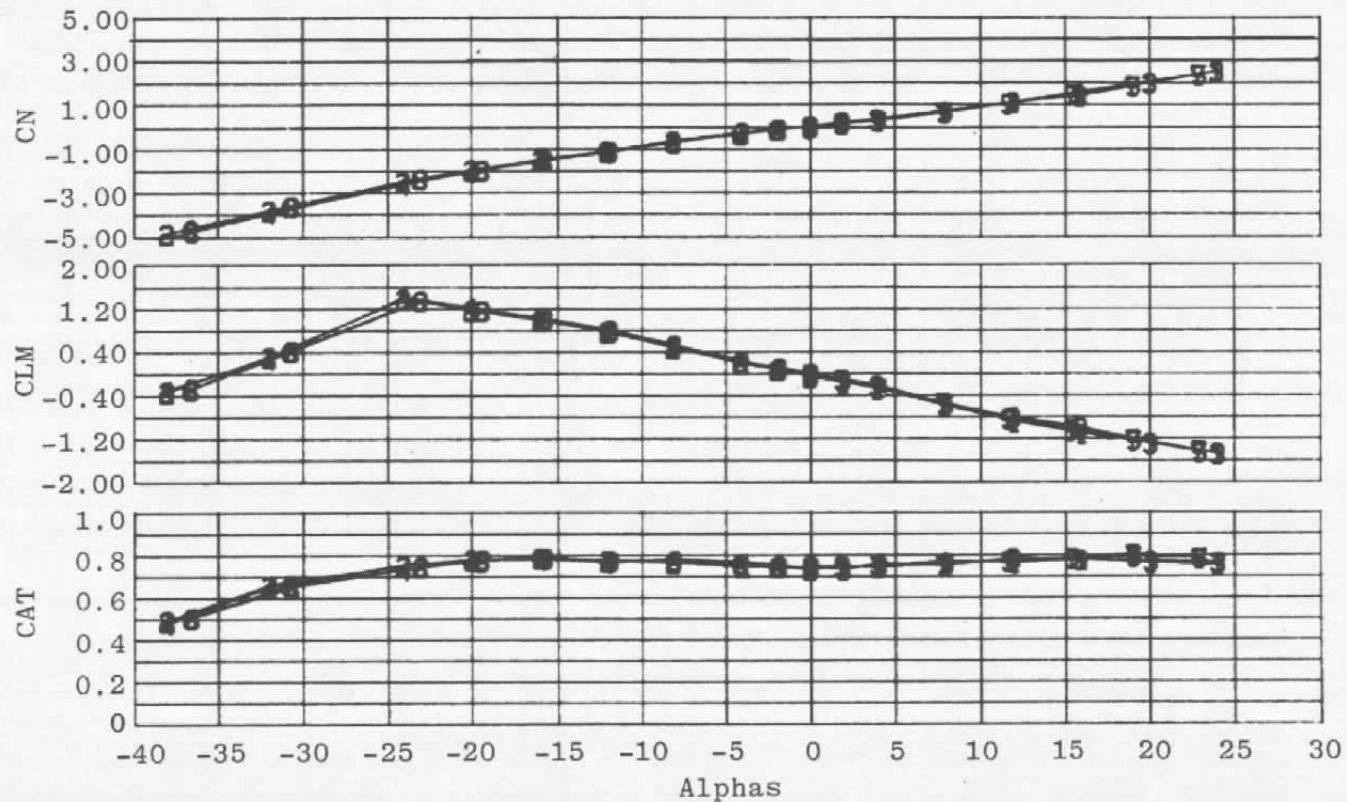


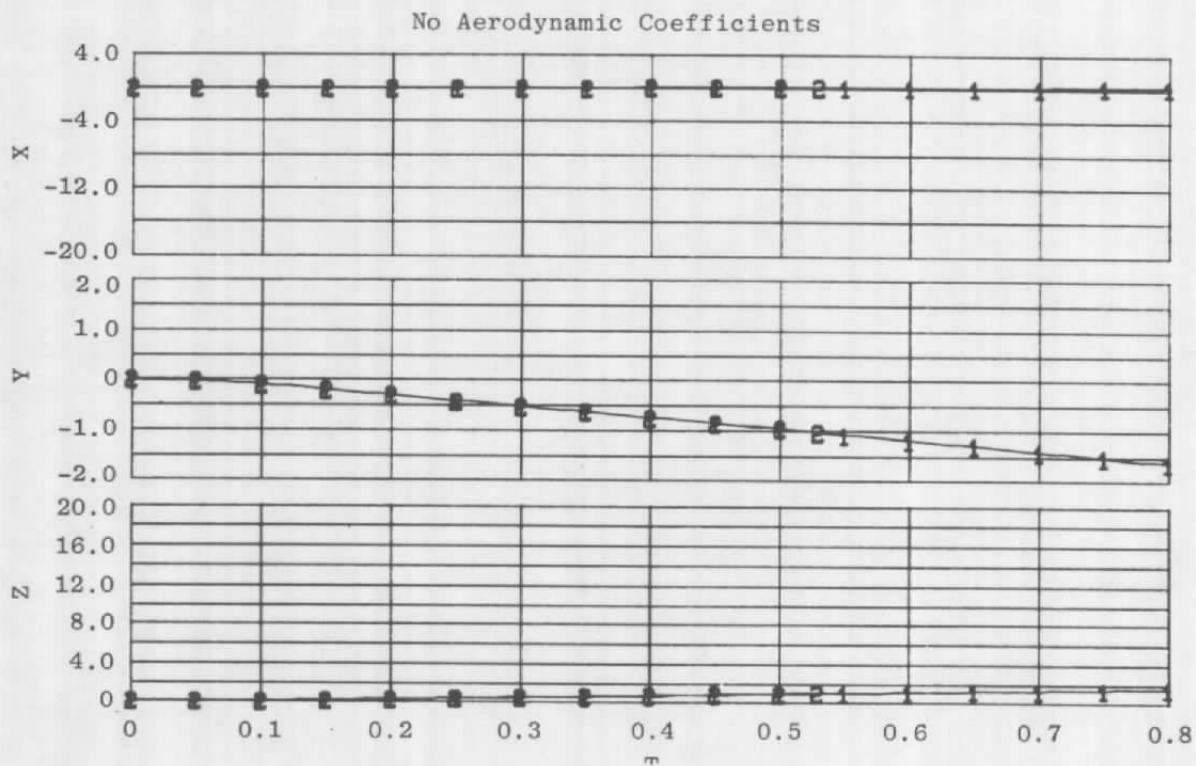
Figure 7. Effect of digital filtering on aerodynamic coefficients for an analog cutoff frequency of 4 Hz.

*** 16T CTS Air-On Demo (Trajectory) ***

Run = 58,917

1 Off-Line Program Using the Trajectory Generation Program

2 Off-Line Program Using the 16T CTS Program in Simulate



a. Linear positions

Figure 8. Comparison of Trajectory Generation Program and 16T CTS program simulated trajectory.

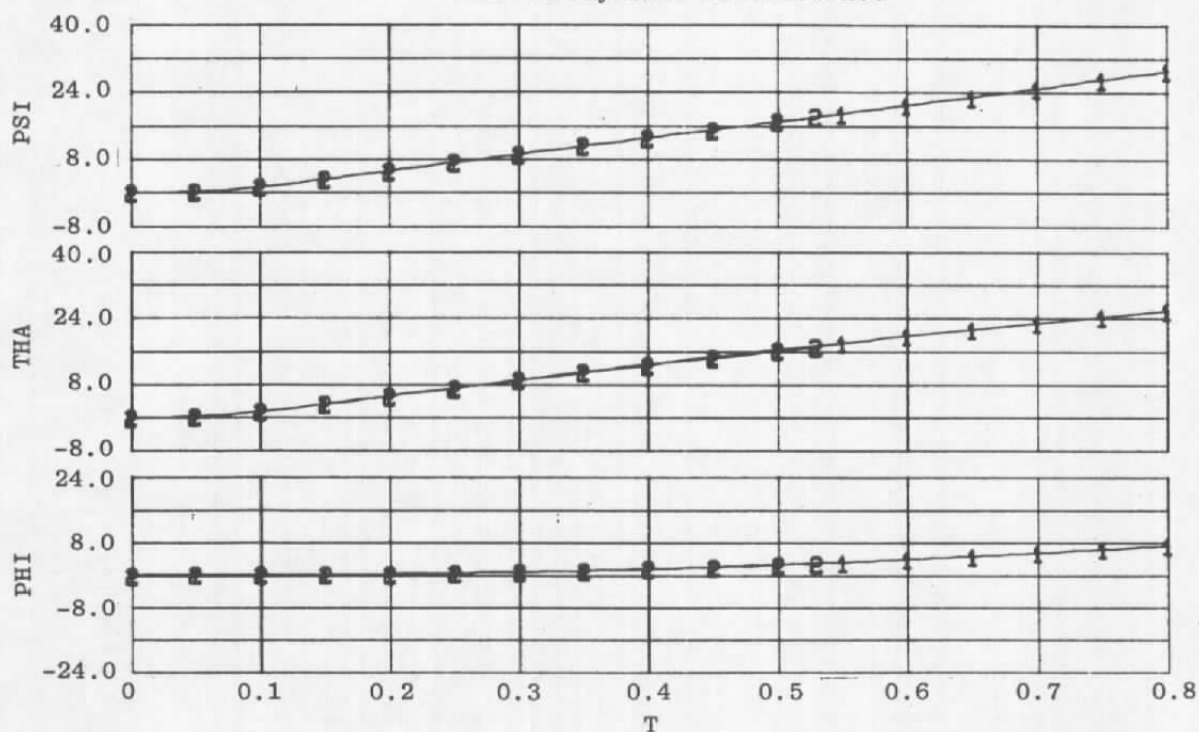
*** 16T CTS Air-On Demo (Trajectory) ***

Run = 58,917

1 Off-Line Program Using the Trajectory Generation Program

2 Off-Line Program Using the 16T CTS Program in Simulate

No Aerodynamic Coefficients



b. Angular positions

Figure 8. Concluded.

*** 16T CTS Air-On Demo (Trajectory) ***
 Run = 87,981
 1 Off-Line Trajectory Using the 16T Free-Stream Aerodynamic
 Coefficient Data
 2 16T On-Line Trajectory Data

Mach = 0.7

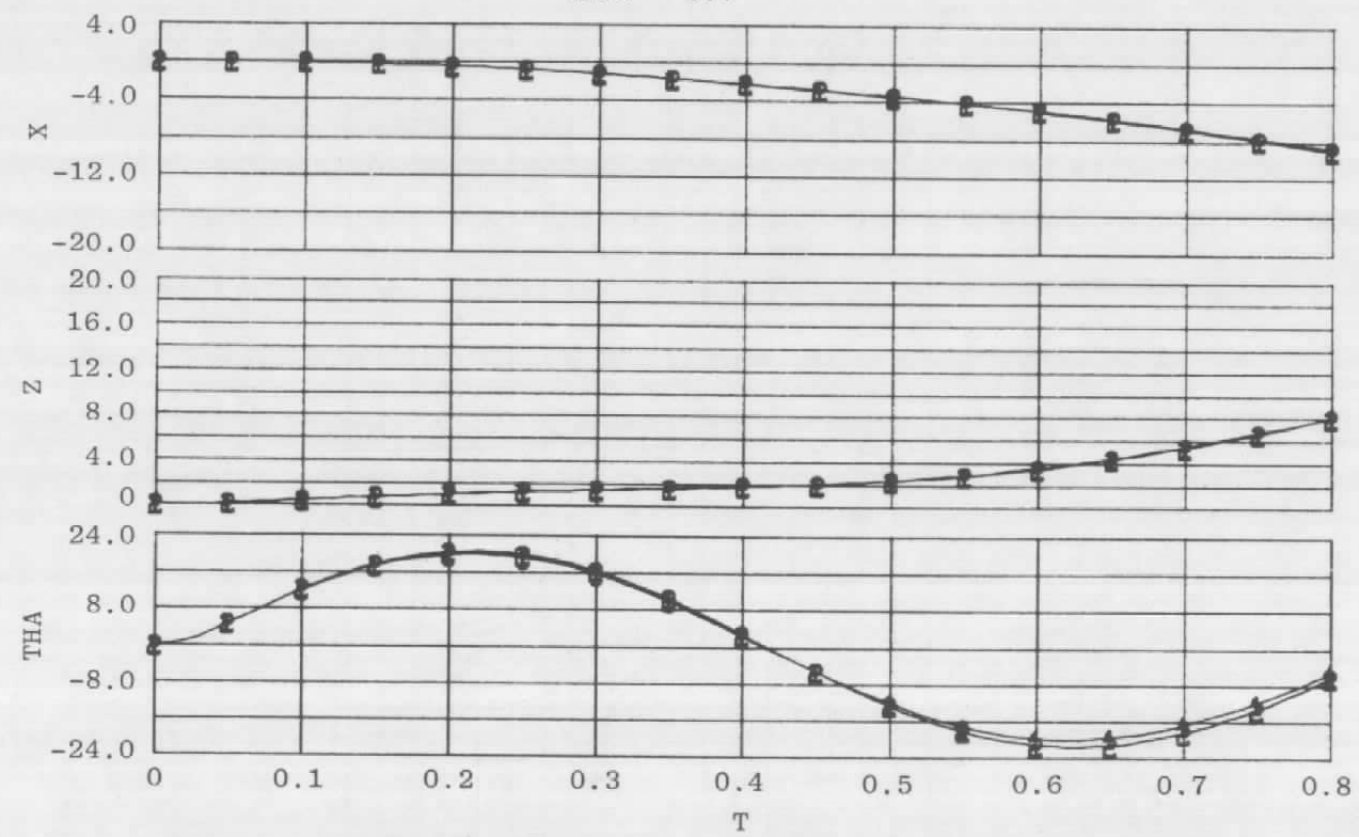


Figure 9. Comparison of a simulated 16T trajectory and an on-line trajectory.

*** 16T CTS Air-On Demo (Trajectory) ***
 Run = 981,985
 1 16T On-Line Trajectory; Move-Pause
 2 16T On-Line Trajectory; Velocity Control

Mach = 0.7

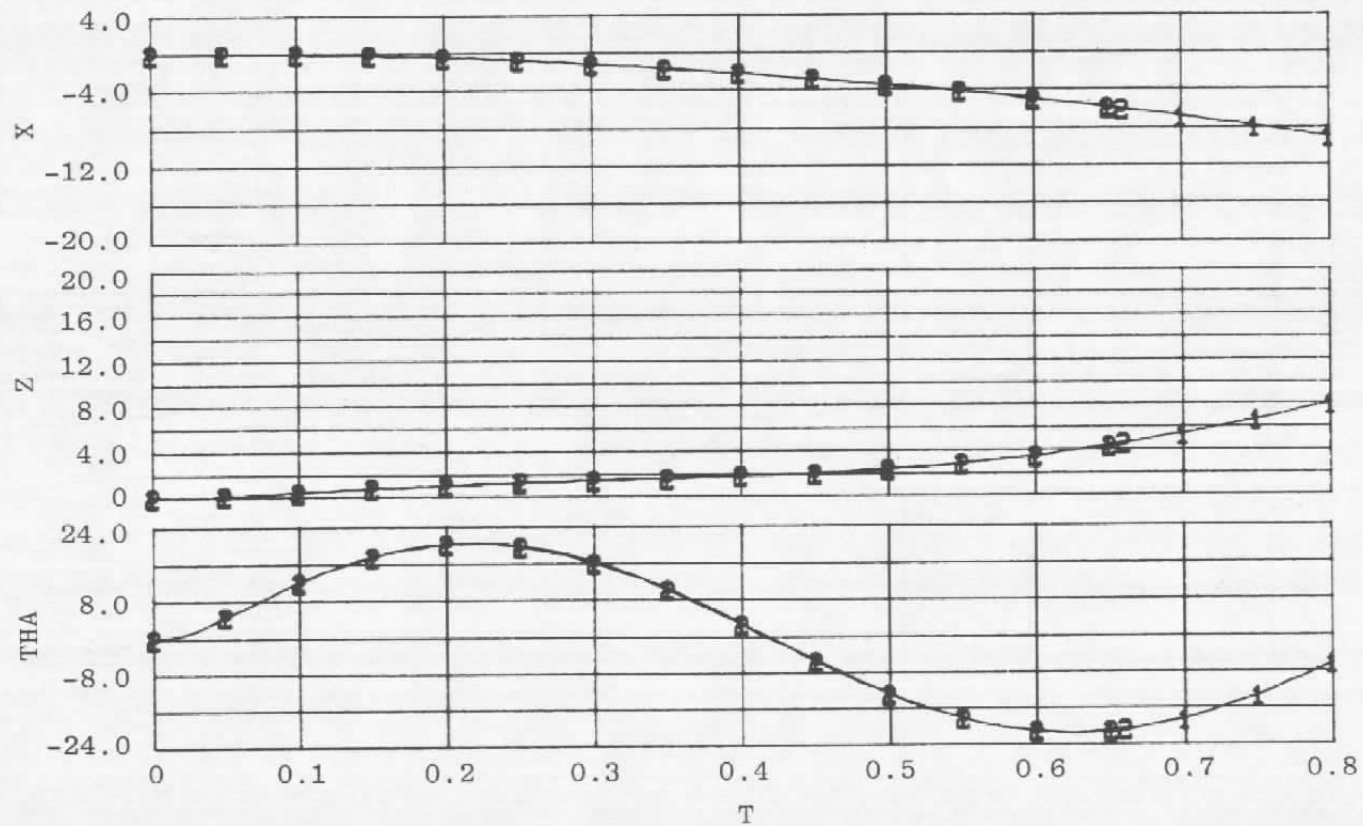


Figure 10. Comparison of on-line trajectories in the move-pause and velocity-control operational modes.

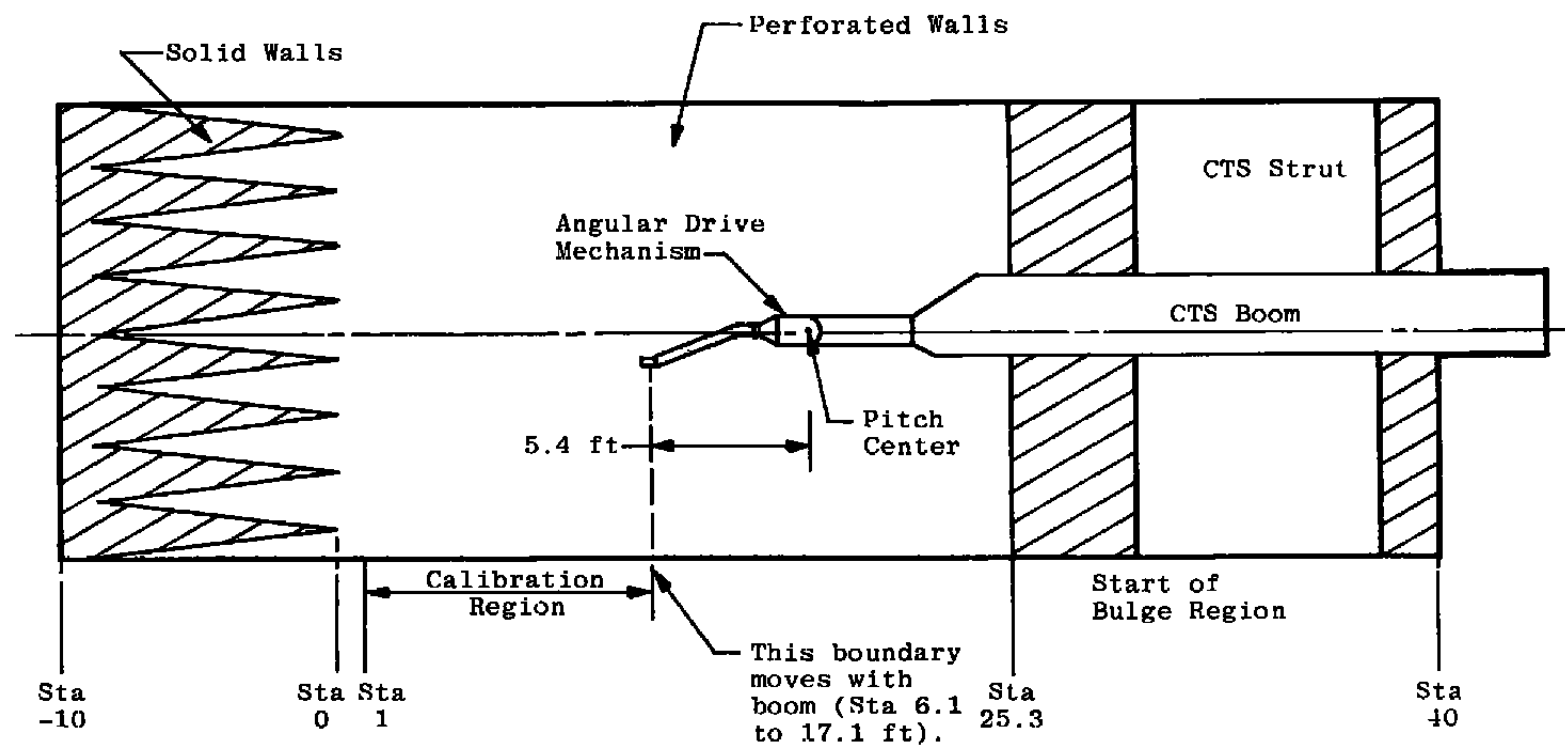


Figure 11. Calibration region in the CTS test section.

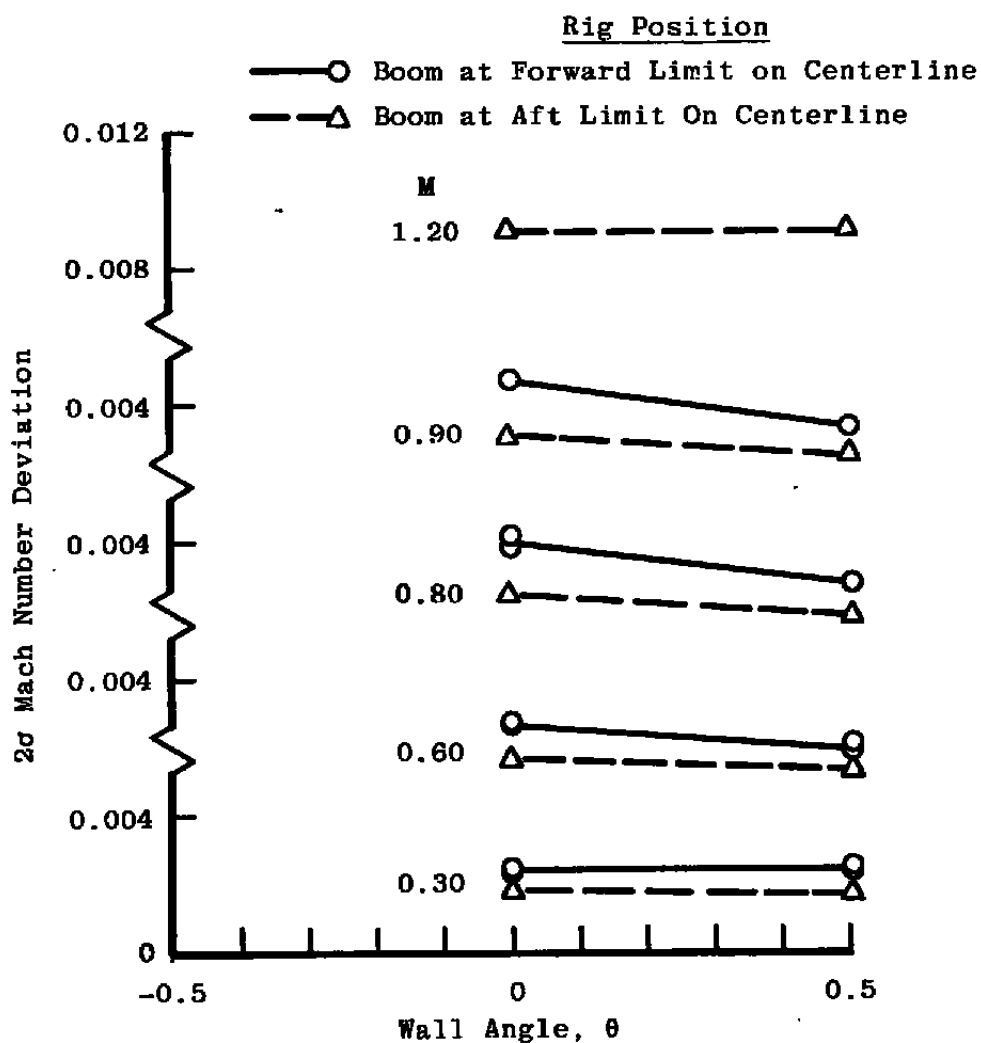
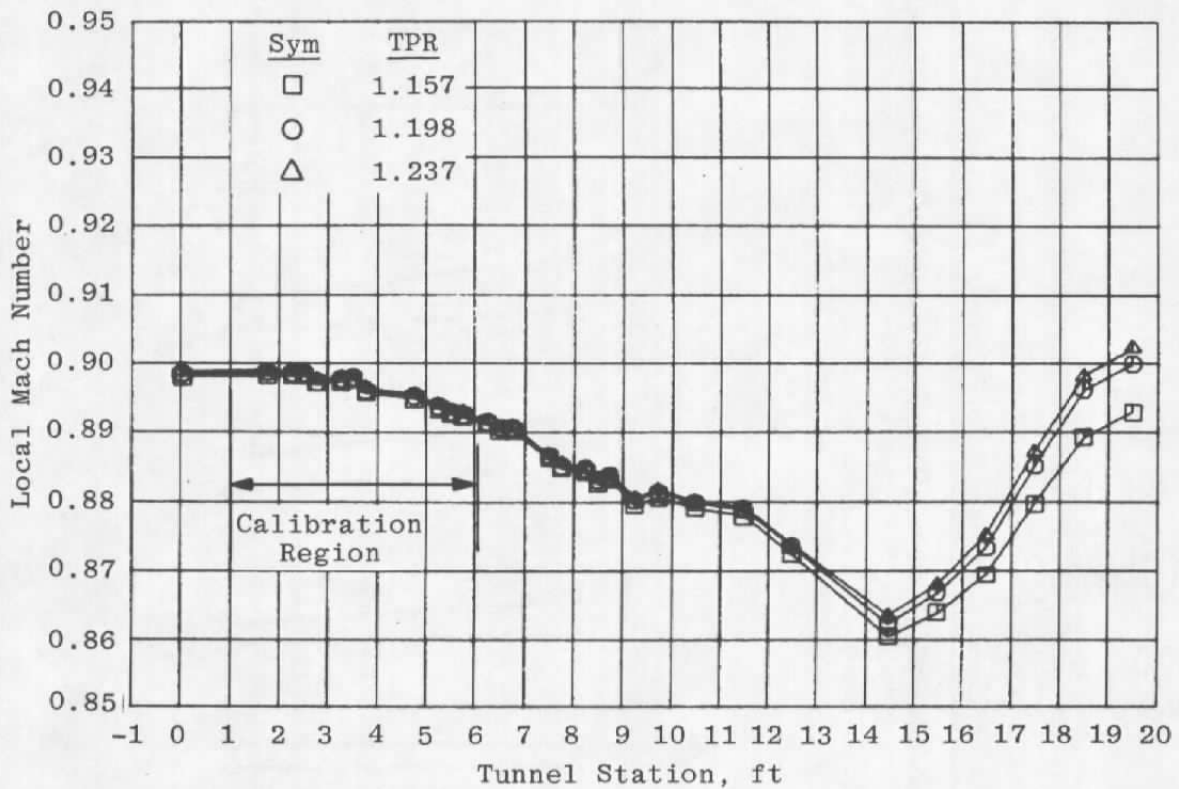
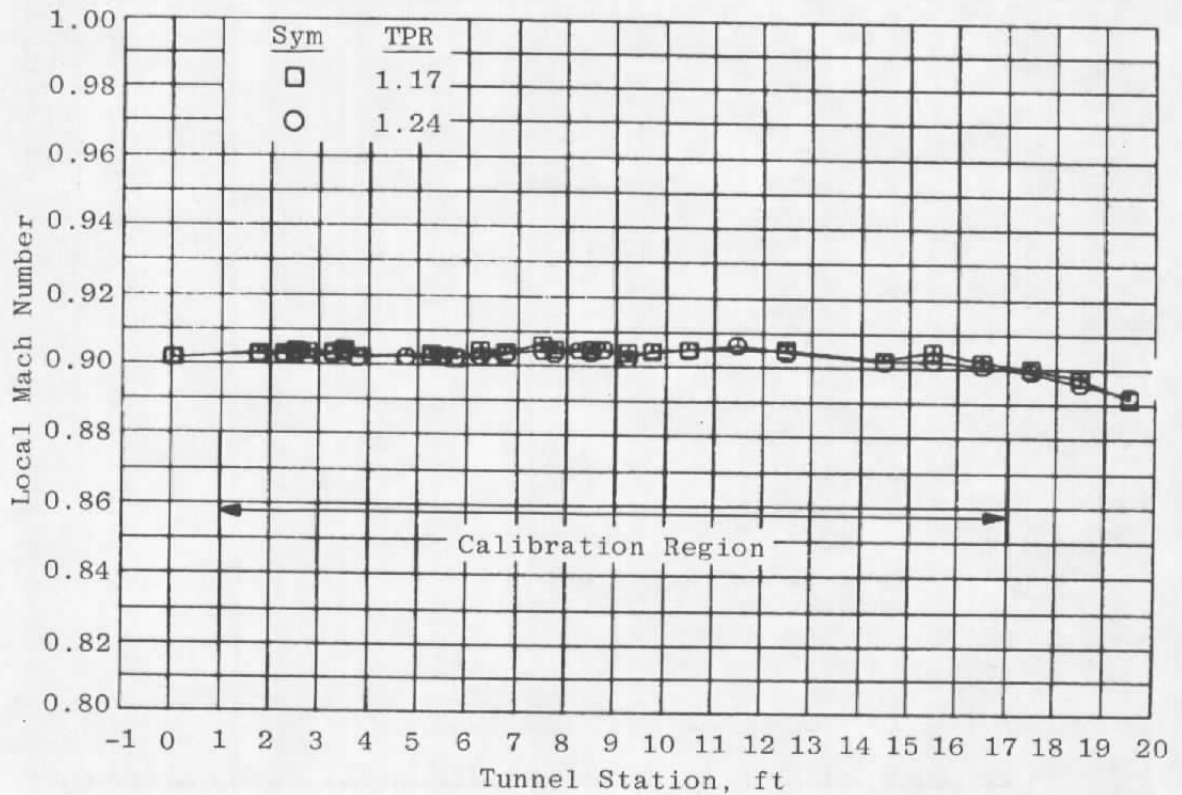


Figure 12. Variation of the 2σ Mach number deviations with test section wall angle.



a. Boom fully forward

Figure 13. Typical effect of tunnel pressure ratio variation on the Mach number distribution $M = 0.90$, $P_T = 1200$ psfa, $\theta = 0.5$ deg.



b. Boom fully aft
Figure 13. Concluded.

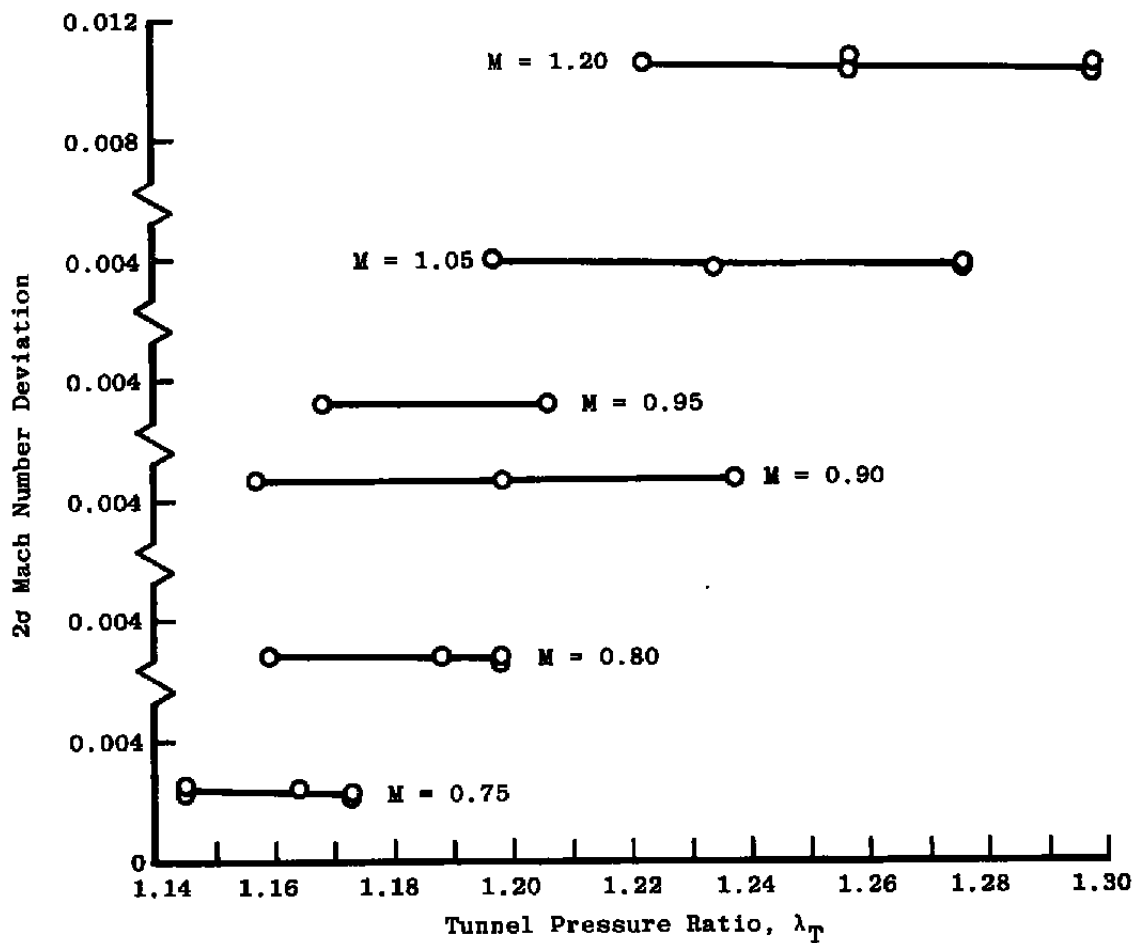


Figure 14. Variation of the 2σ Mach number deviation with tunnel pressure ratio, $P_T = 1200$ psfa, $\theta = 0.5$ deg.

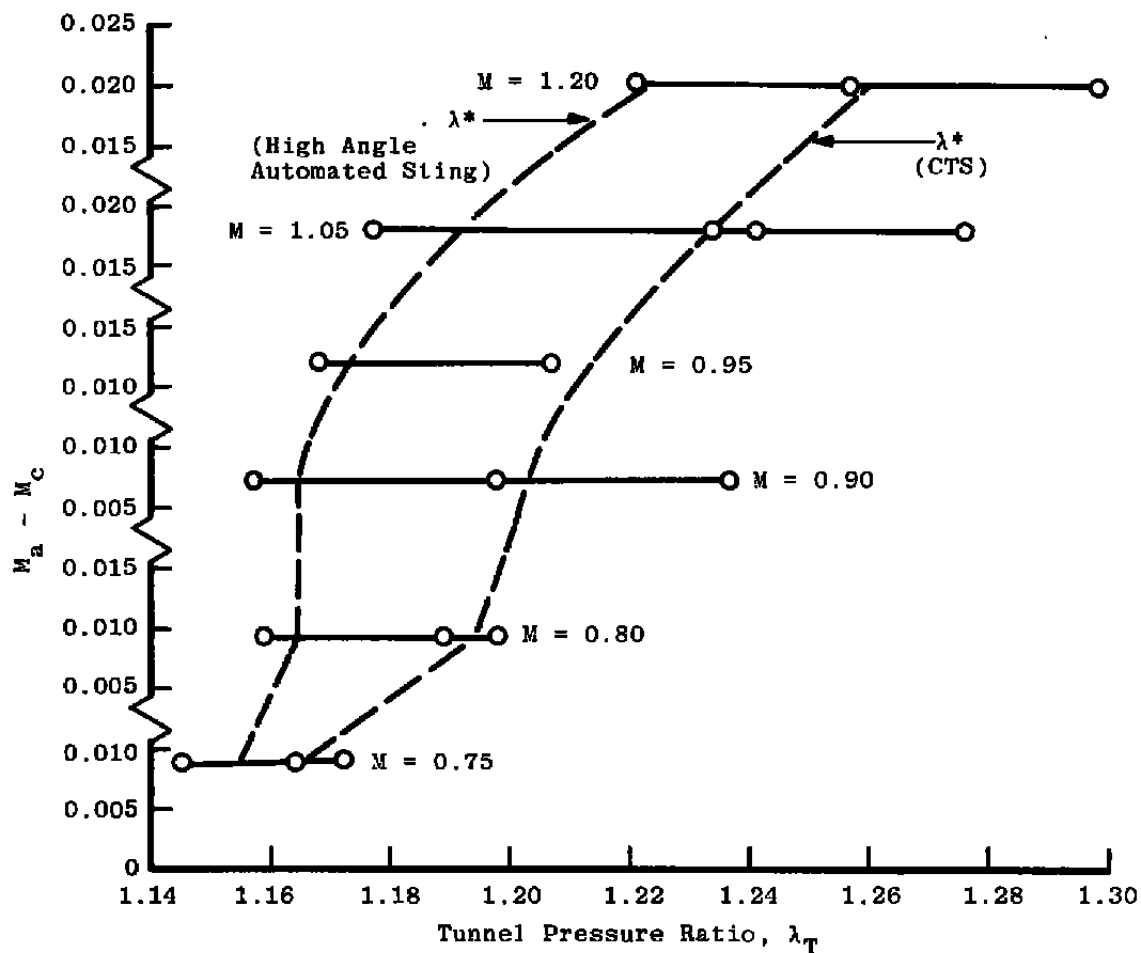
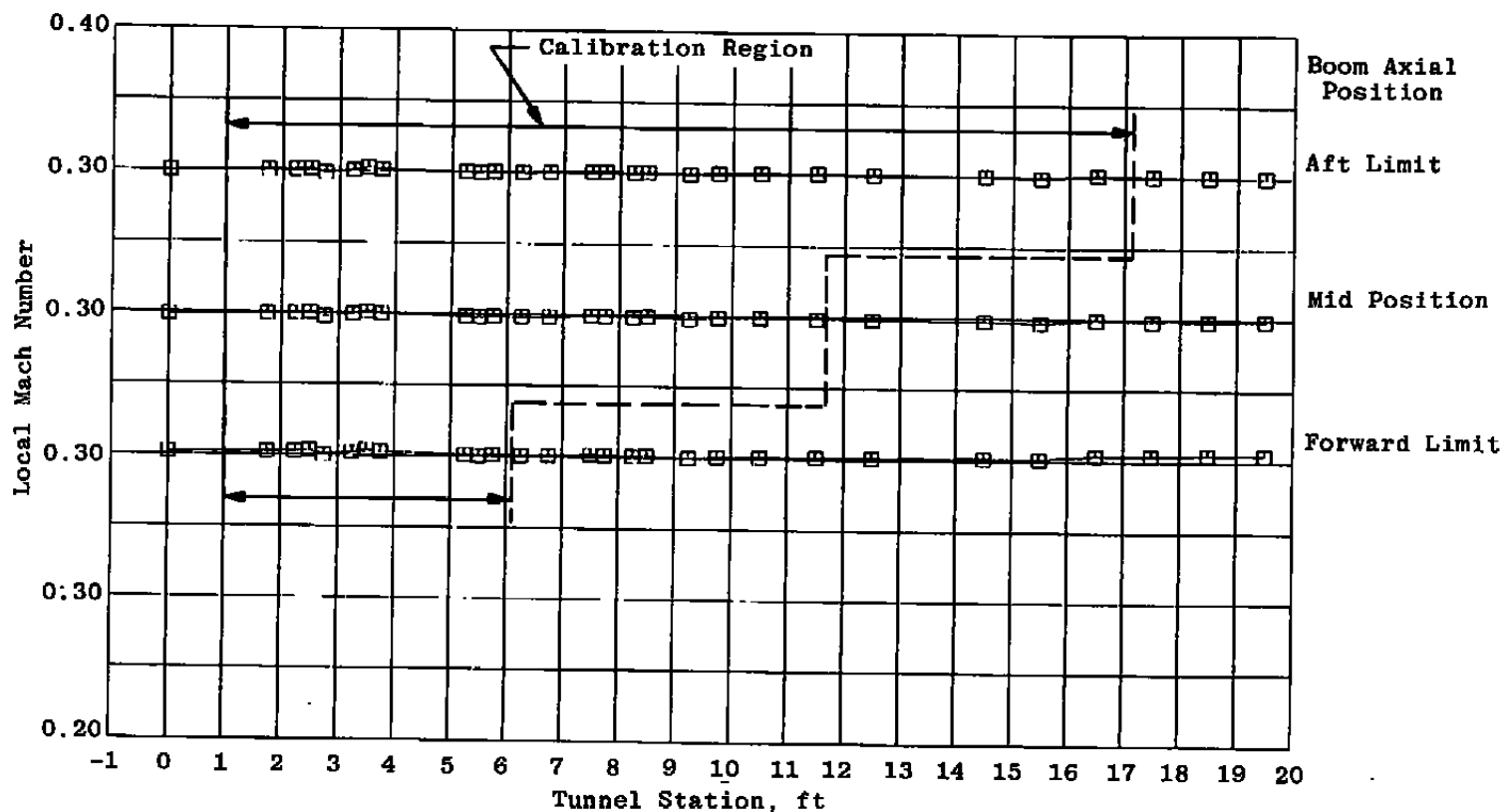
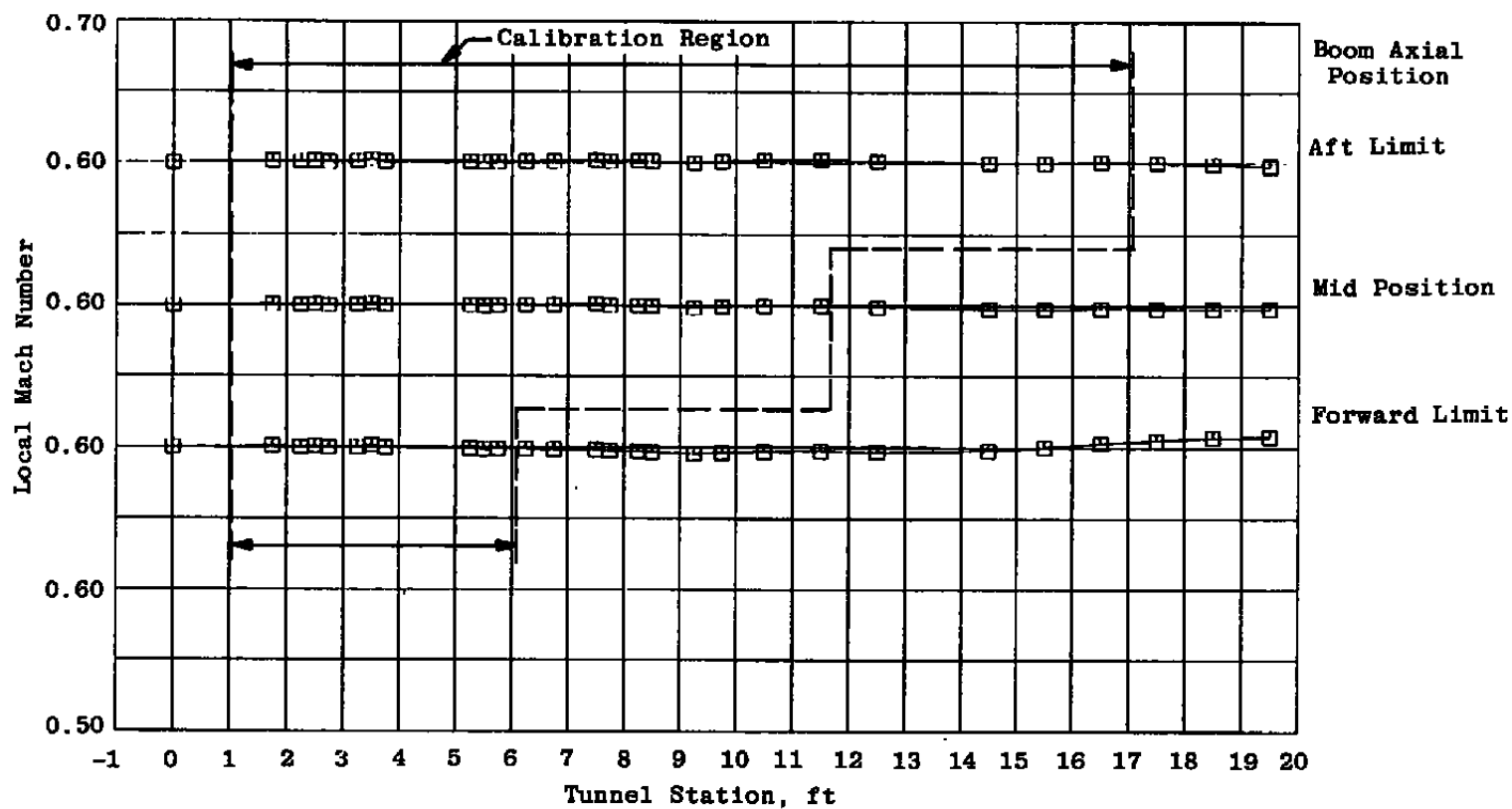


Figure 15. Variation of the calibration parameter with tunnel pressure ratio, $P_T = 1200$ psfa, $\theta = 0.5$ deg.



a. $M = 0.30$

Figure 16. The variation of Mach number distribution with boom axial position,
 $P_T = 1200$ psfa, $\theta = 0.5$ deg, $Y = 0$ ft, $Z = 0$ ft.



b. $M = 0.60$
Figure 16. Continued.

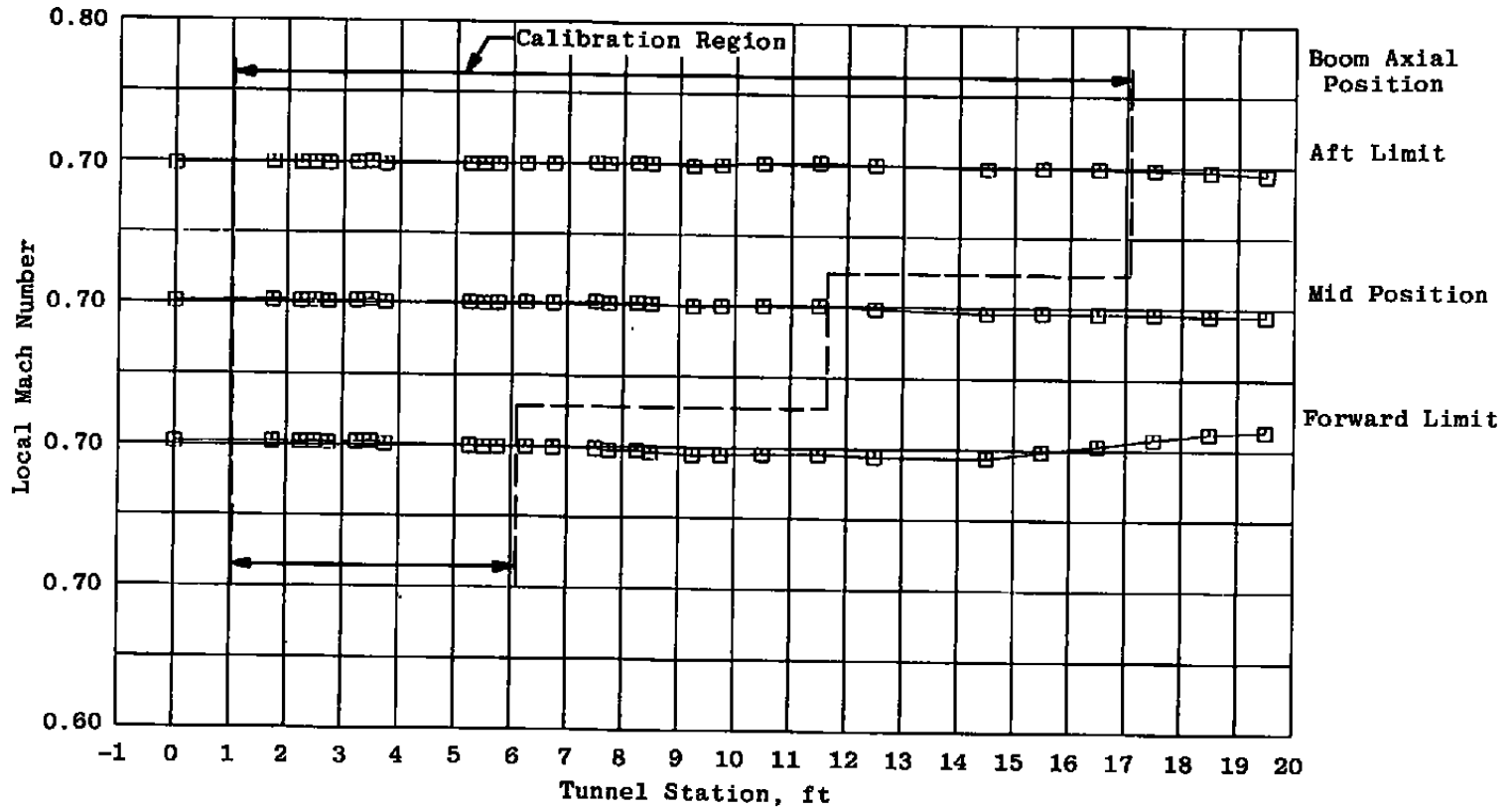
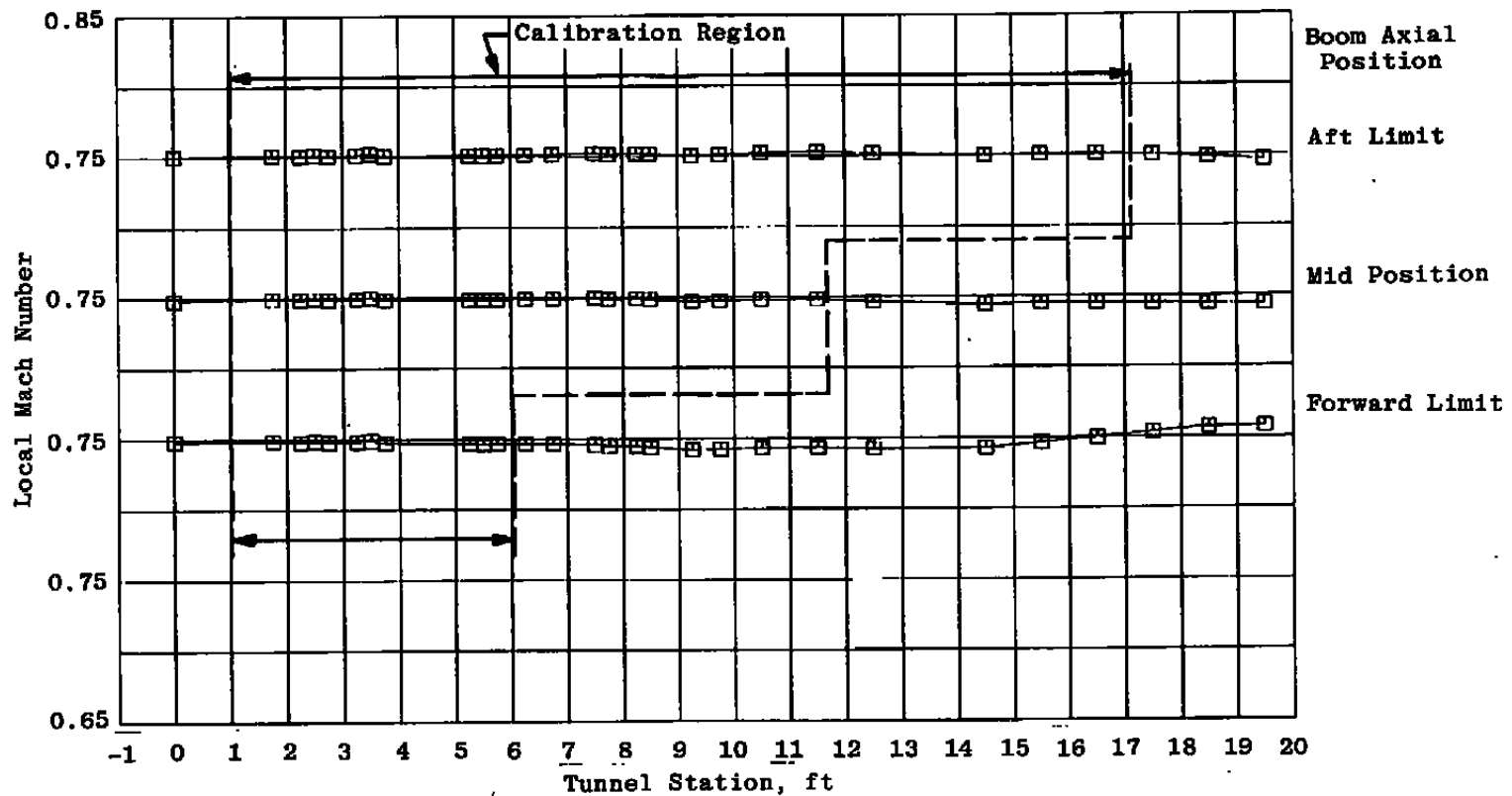
c. $M = 0.70$

Figure 16. Continued.



d. $M = 0.75$
Figure 16. Continued.

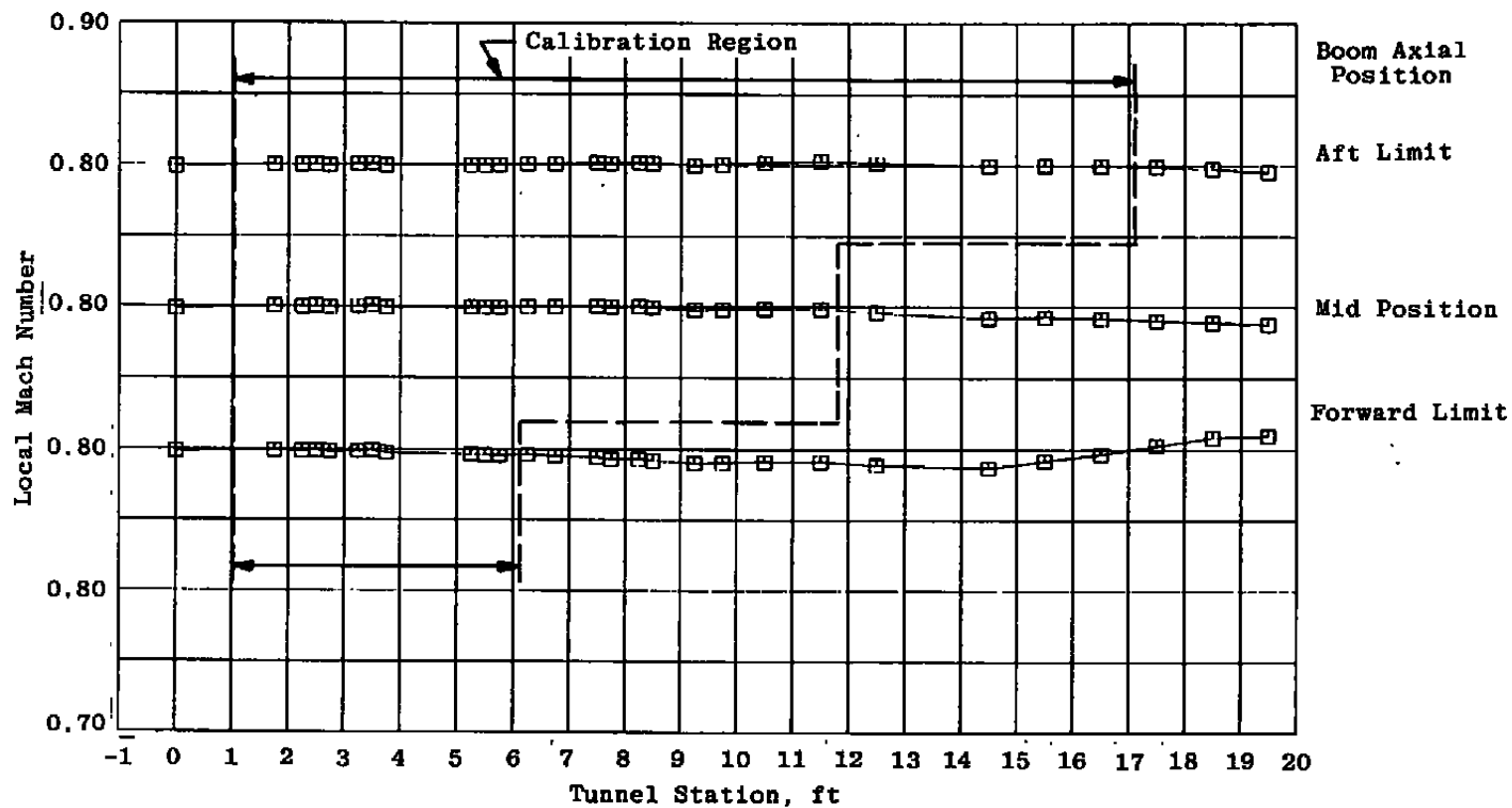
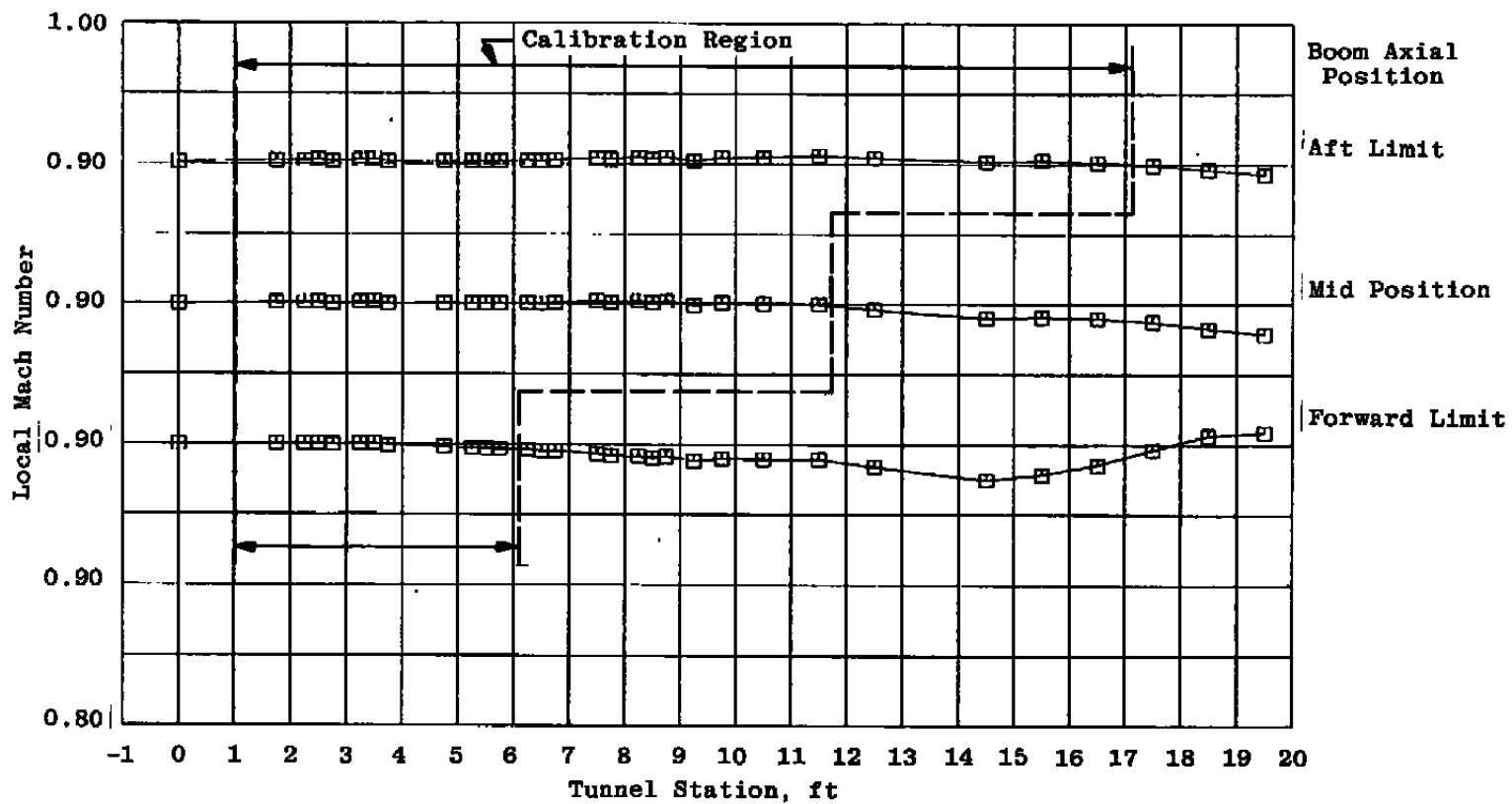
e. $M = 0.80$

Figure 16. Continued.



f. $M = 0.90$
Figure 16. Continued.

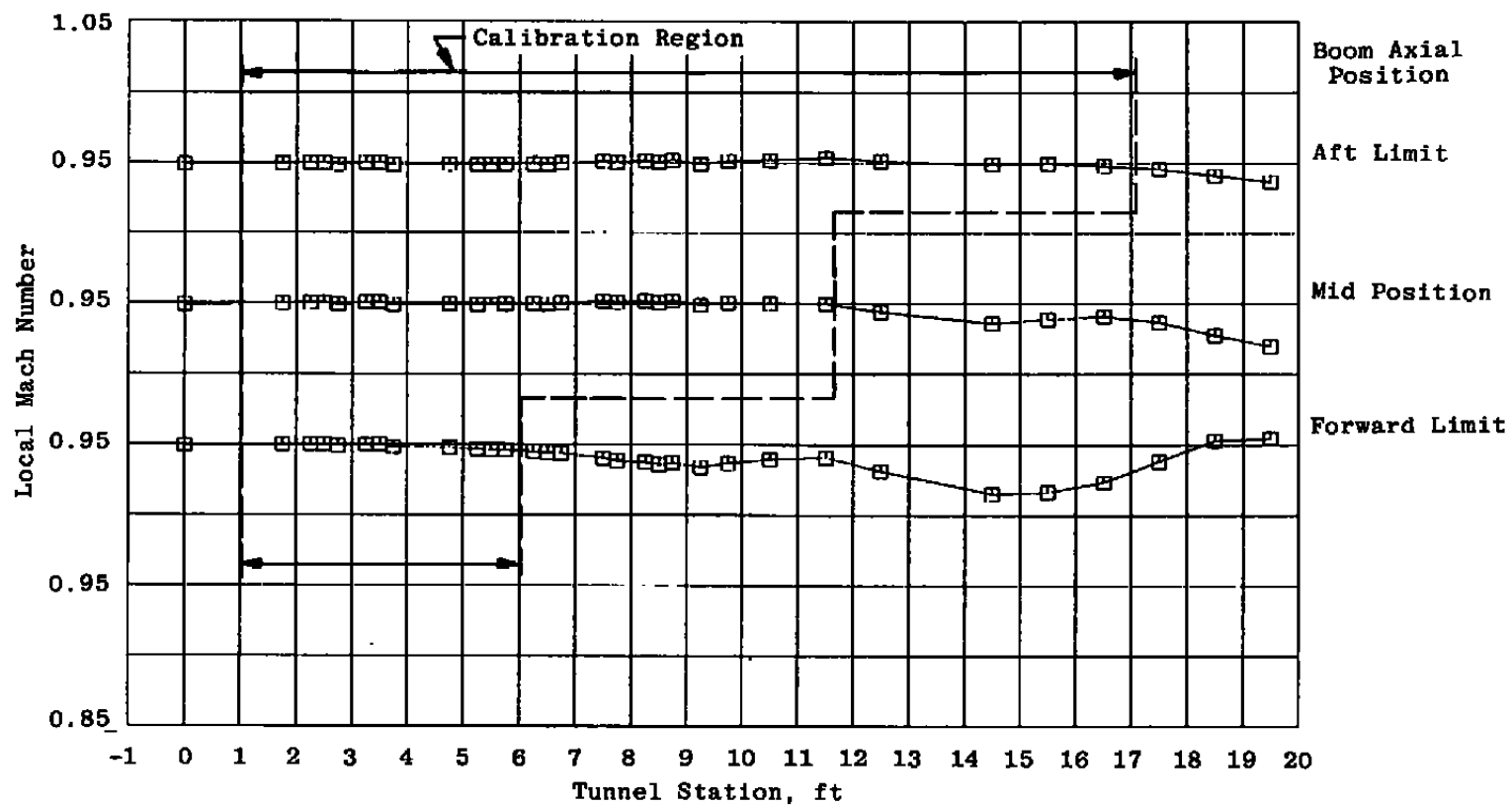
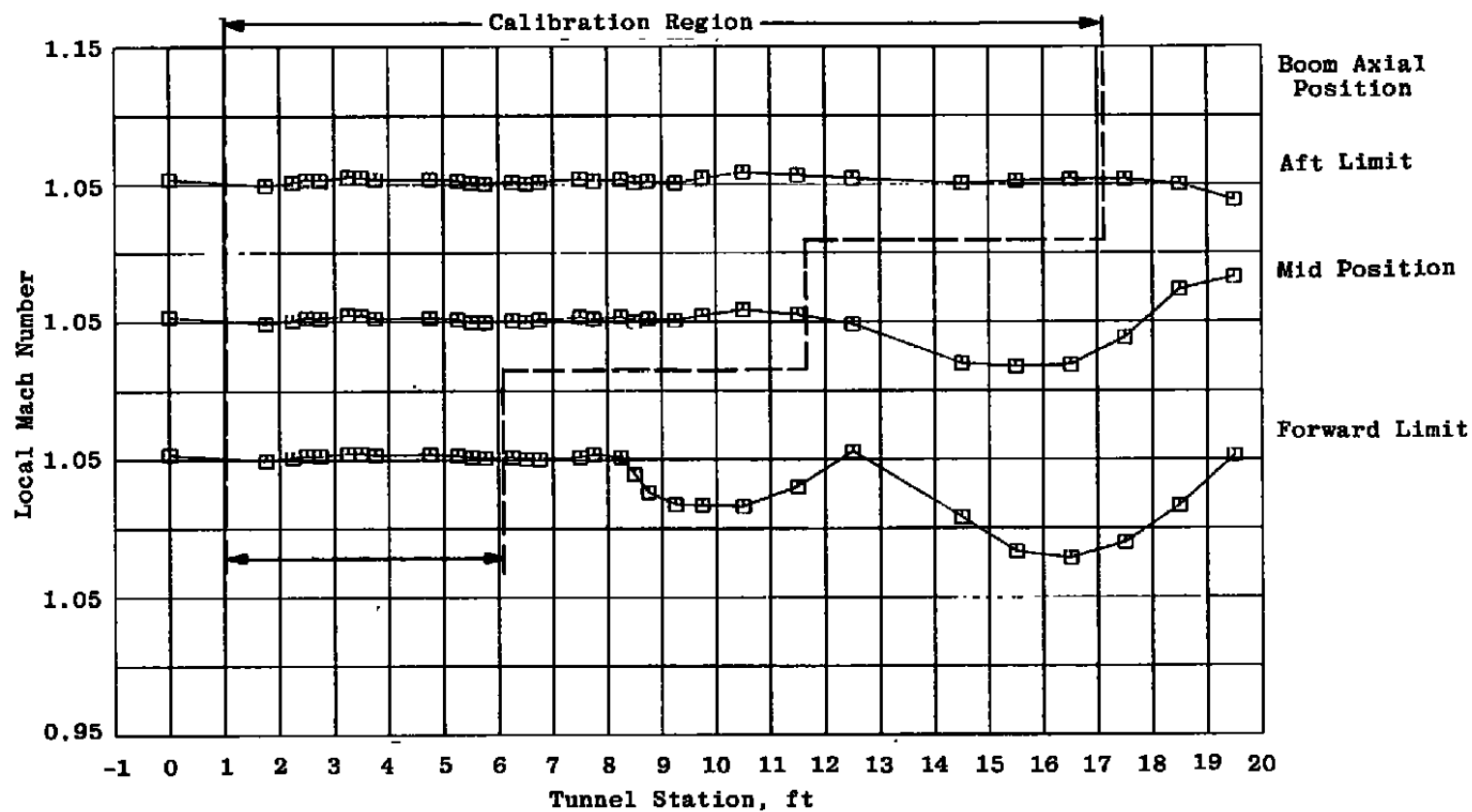
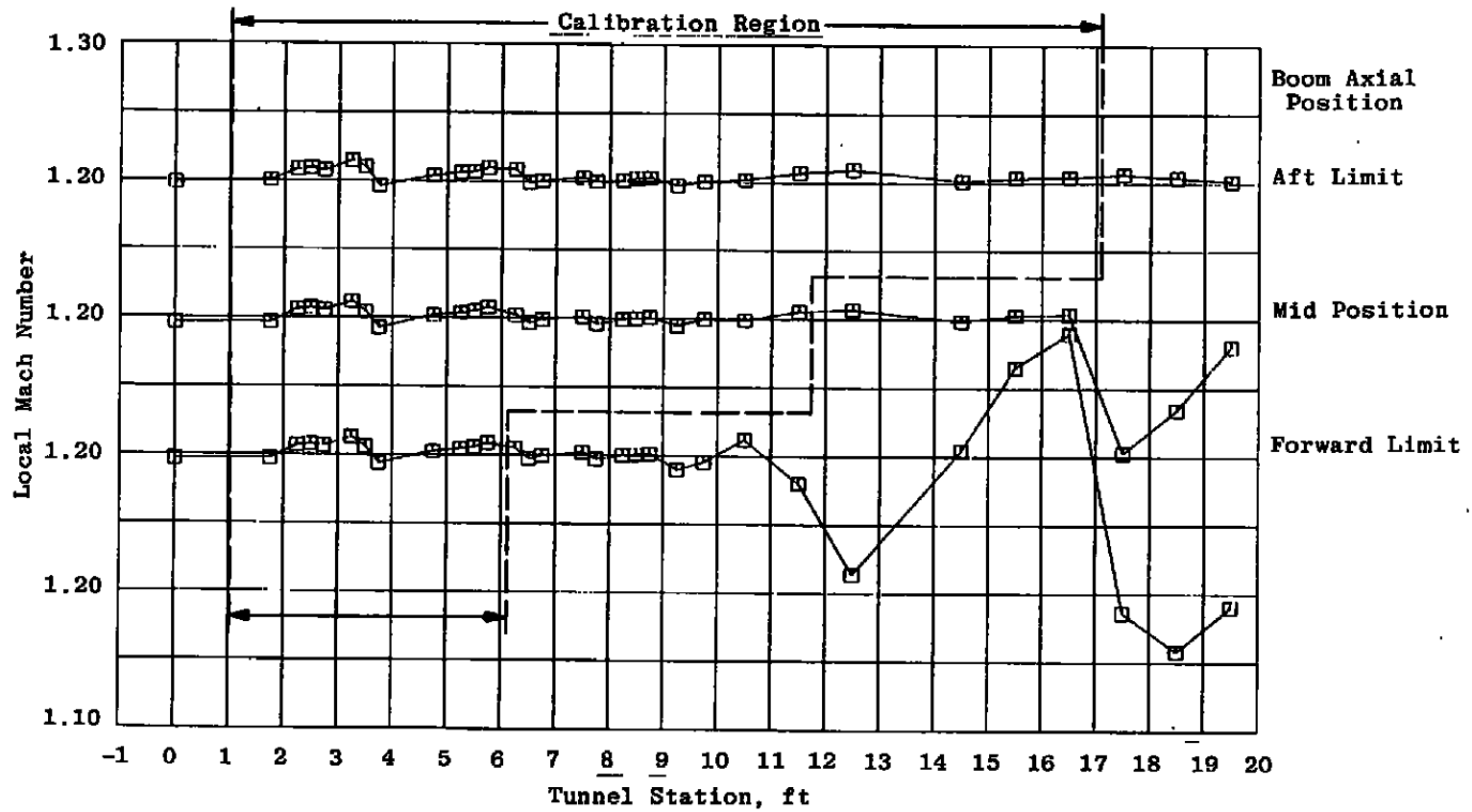
g. $M = 0.95$

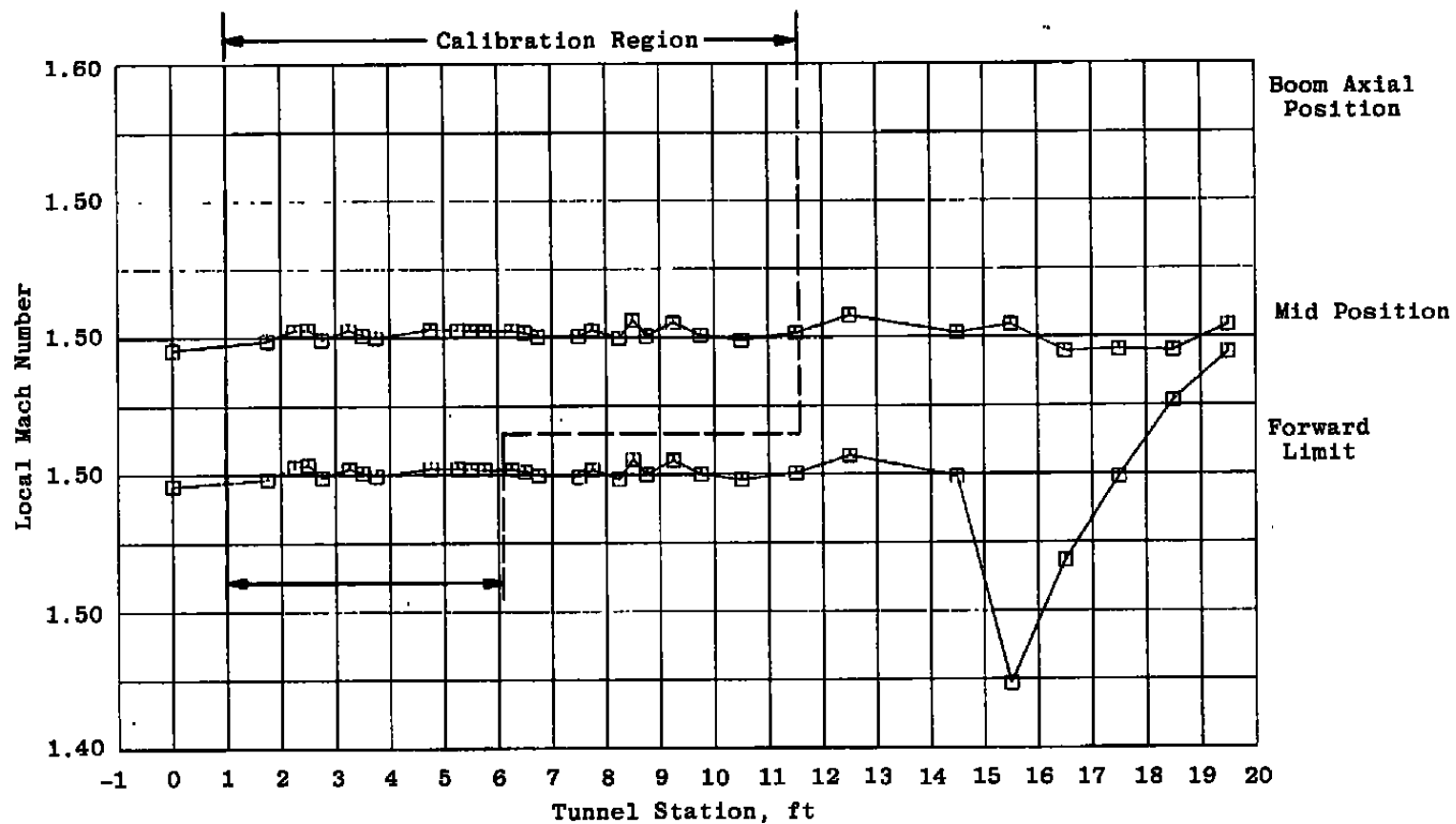
Figure 16. Continued.



h. $M = 1.05$
Figure 16. Continued.



i. $M = 1.20$
Figure 16. Continued.



j. $M = 1.50$
 Figure 16. Concluded.

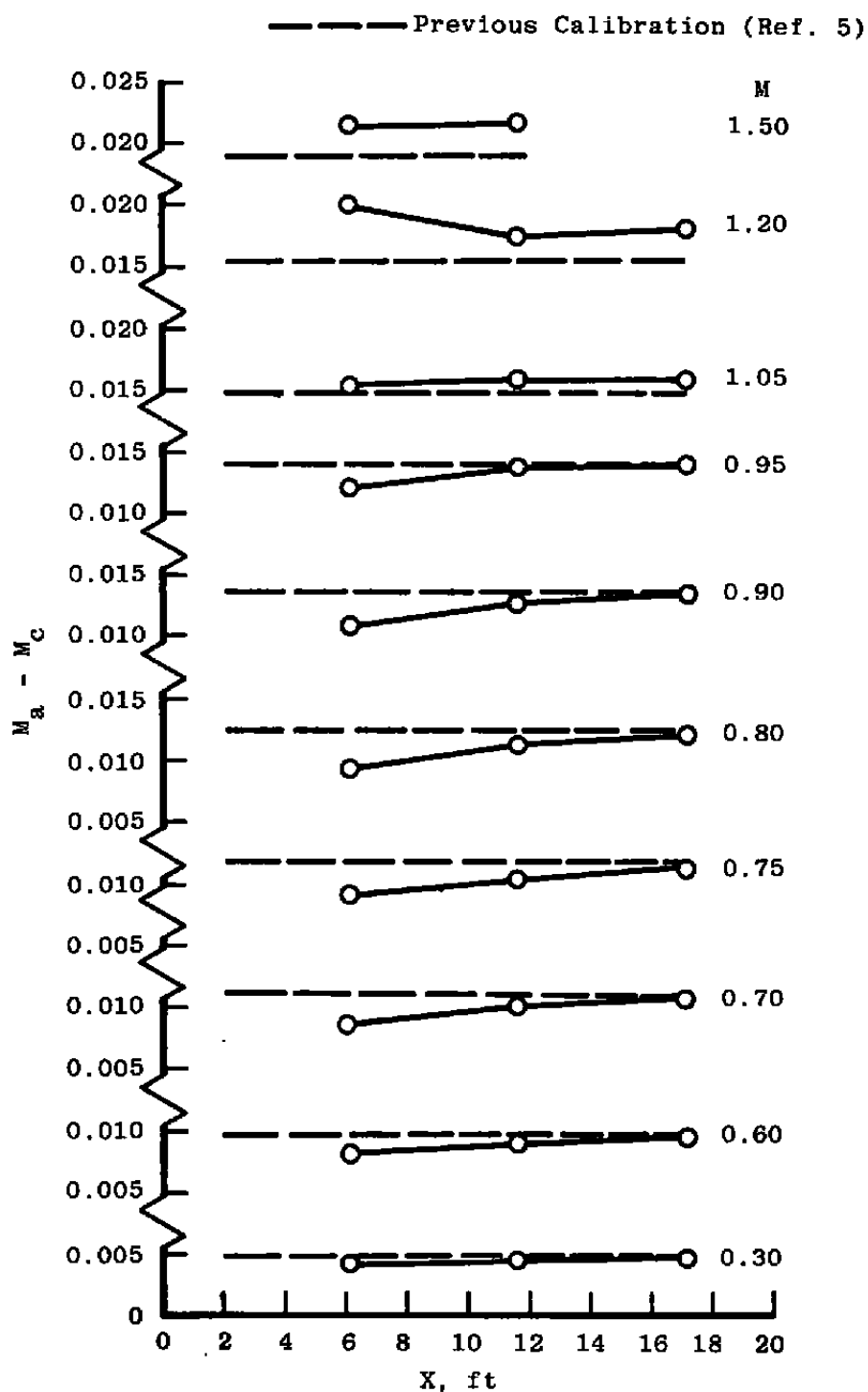
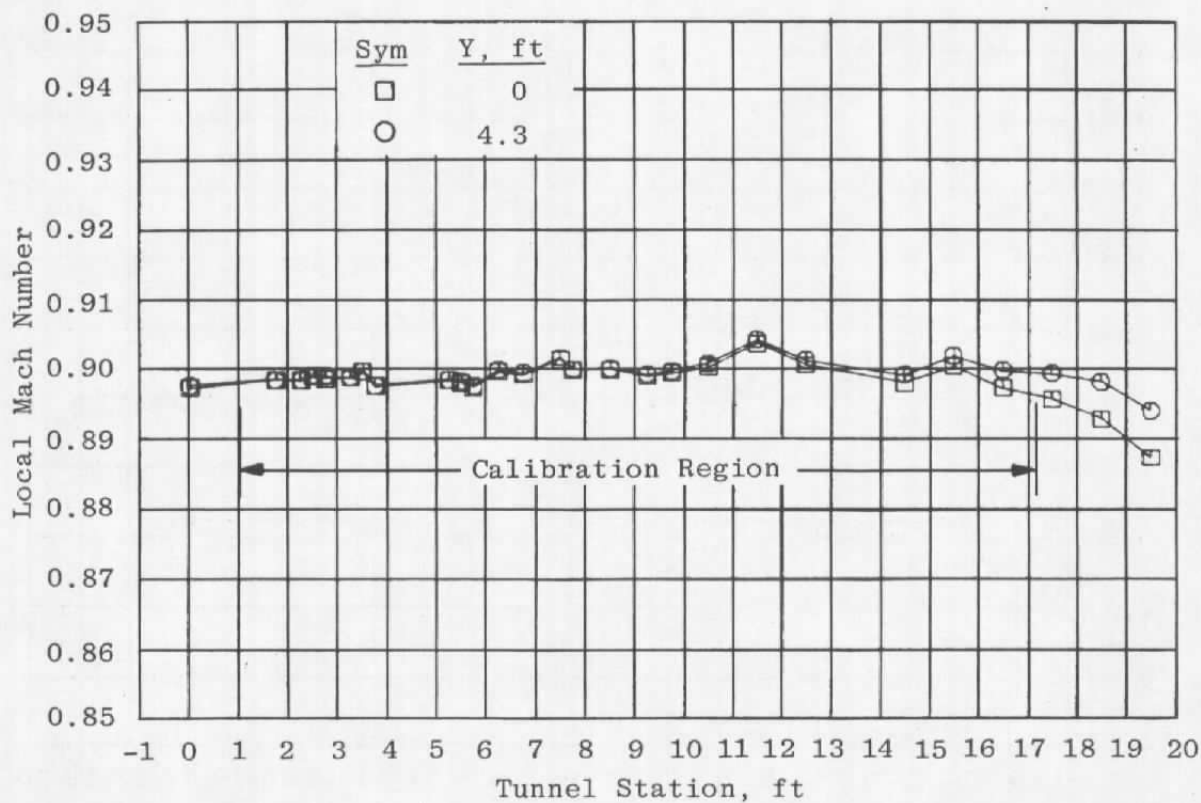
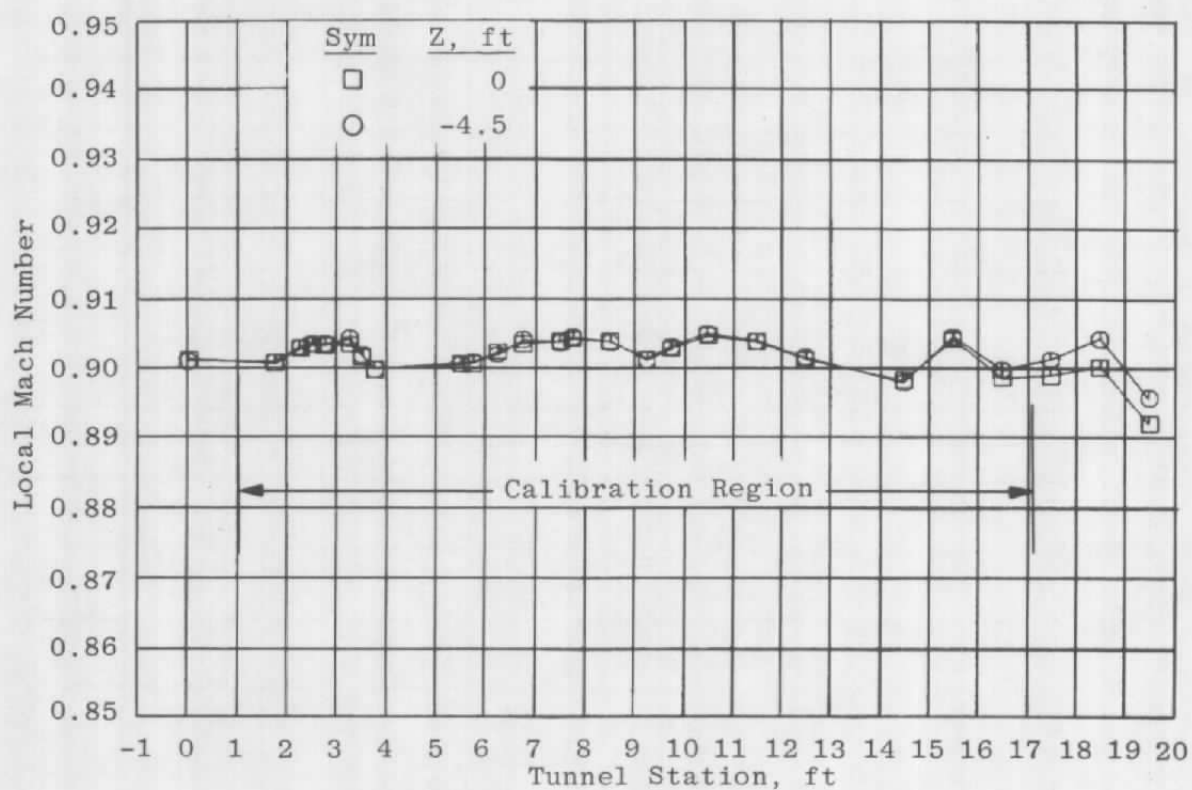


Figure 17. Variation of the calibration parameter with boom axial position,
 $P_T = 1200$ psfa, $\theta = 0.5$ deg, $Y = 0$ ft, $Z = 0$ ft.

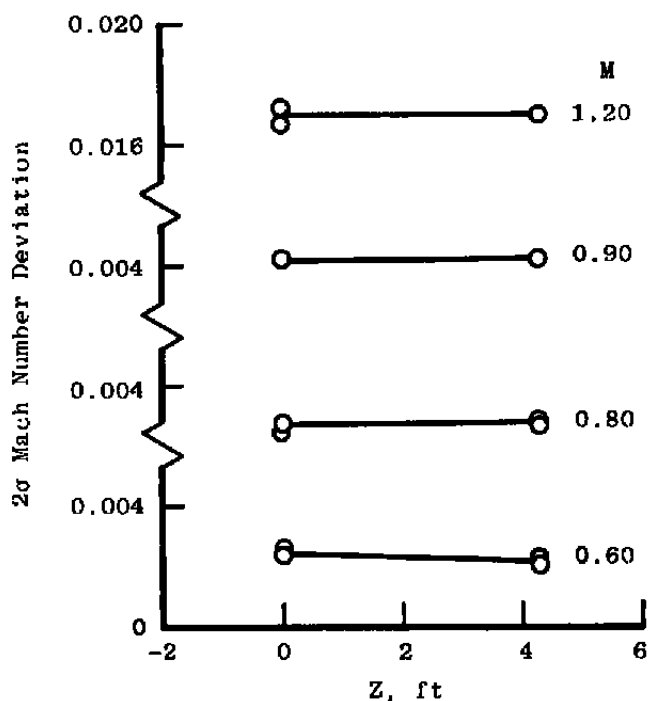


a. Boom vertical position variation

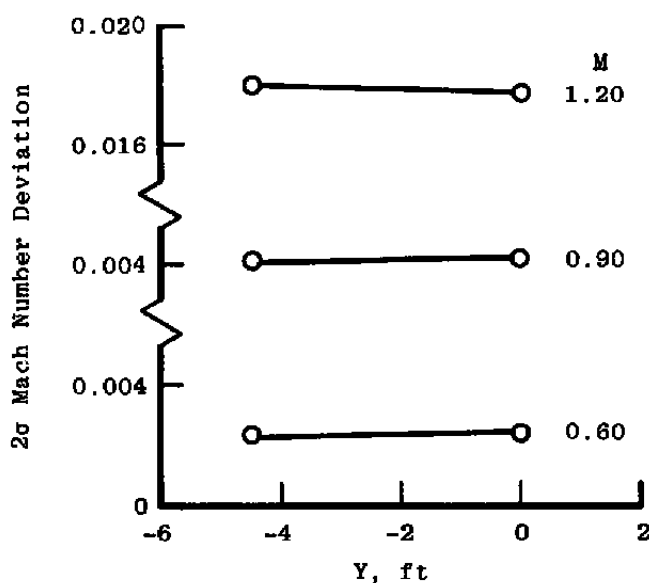
Figure 18. Typical effect of vertical and horizontal movement of the CTS on the Mach number distribution, $P_T = 1200$ psfa, $\theta = 0.5$ deg.



b. Boom horizontal position variation
Figure 18. Concluded.

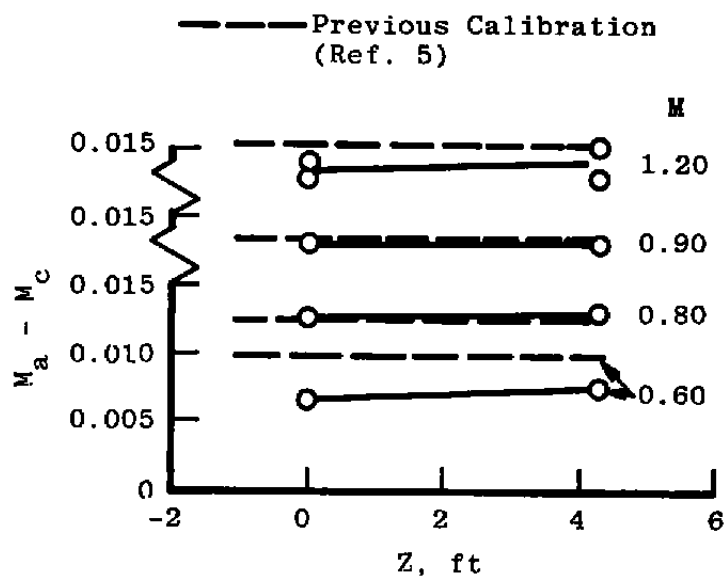


a. Vertical variation of boom position

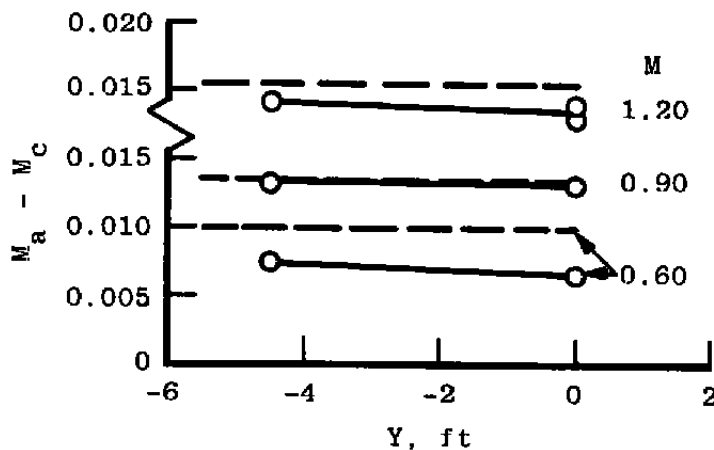


b. Horizontal variation of boom position

Figure 19. Variation of the 2σ Mach number deviation with vertical and horizontal movement of the CTS, $P_T = 1200$ psfa, $\theta = 0.5$ deg.



a. Vertical variation of boom position



b. Horizontal variation of boom position

Figure 20. Variation of the calibration parameter with vertical and horizontal movement of the CTS, $P_T = 1200$ psfa, $\theta = 0.5$ deg.

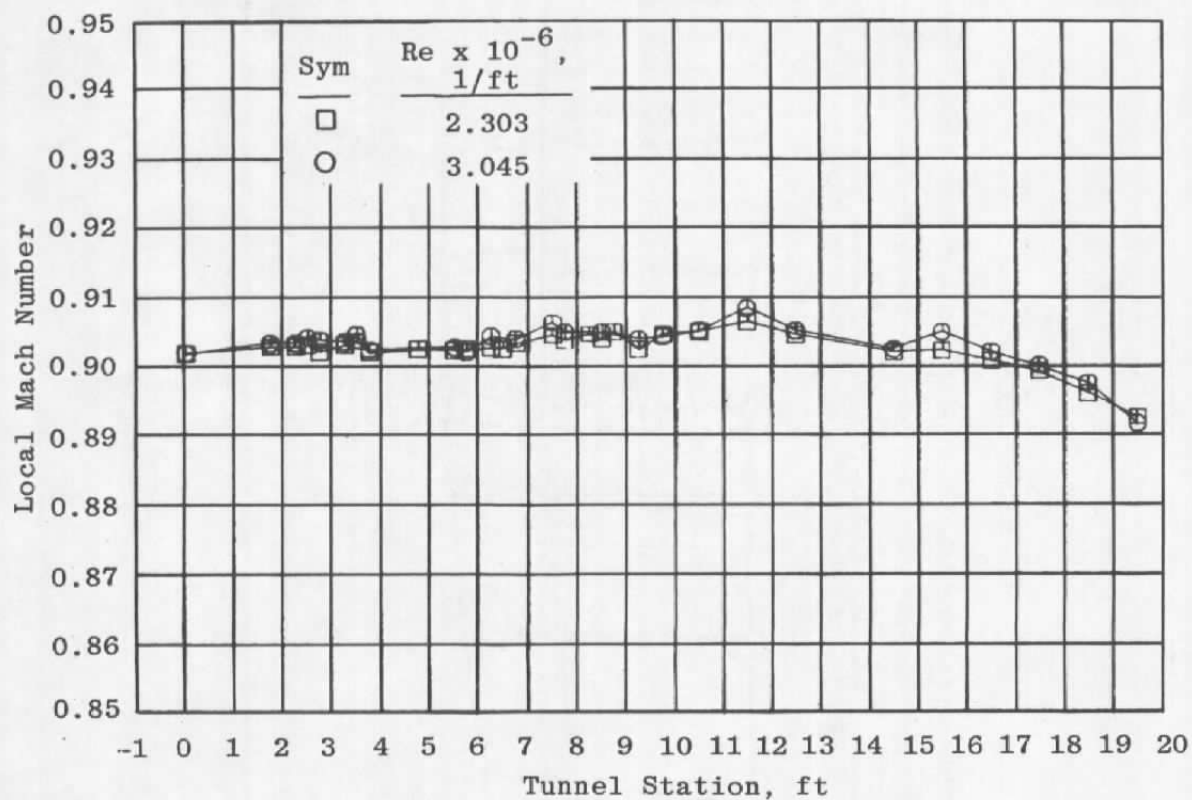


Figure 21. Typical effect of Reynolds number variation on the Mach number distribution, $P_T = 1200$ psfa, $\theta = 0.5$ deg.

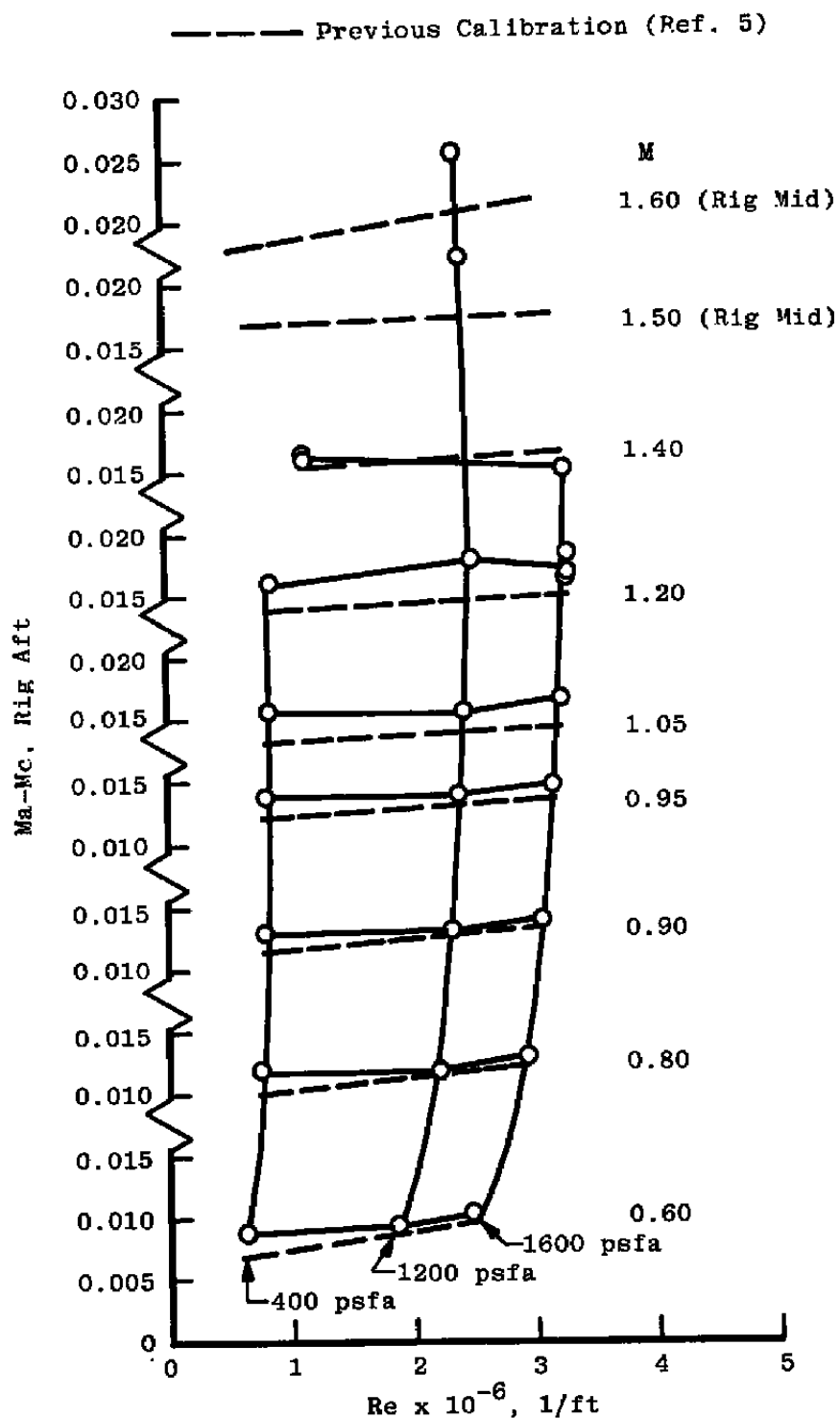


Figure 22. Variation of the calibration parameter with Reynolds number, $\theta = 0.5$ deg.

Table 1. Grid and Trajectory Run Matrix

Run	Mach	PT	Alpha	Config	Comments
953	0.9	1200	---	2	GRID - Flow Angle Checks
954 - 967	↓	574	---	↓	GRID - Digital Filtering
968 - 969	↓	↓	---	↓	GRID - Flow Angle Checks
972 - 975	↓	↓	---	↓	GRID - Digital Filtering
981	0.7	1419	---	↓	TRAJECTORY - Digital Filtering
1103	↓	1200	0	3	TRAJECTORY - With Flat Plate BETA = 0
1104 - 1105	↓	↓	5	4	TRAJECTORY - With Flat Plate BETA = -10
1110	1.1	↓	↓	↓	TRAJECTORY - With Flat Plate BETA = -10

Table 2. Configuration Identification Description

Config.	Description
1	Calibration and structural integrity - CTS with 10-in. offset roll - no balance, no aircraft
2	Grid and trajectory verification - 1/4-scale MVB on 10-in. offset roll mechanism - no GAM II strut
3	Grid and trajectory verification - flat plate "aircraft" installed - launch MVB from 0-deg yaw pylon
4	Grid and trajectory verification - flat plate "aircraft" installed - launch MVB from 10-deg yaw pylon

Table 3. Calibration Phase Test Condition Matrix

θ	PT	Mach
0.0	400	0.8
0.0	1200	0.3 - 1.2
0.5	400	0.6 - 1.2
0.5	550	1.4
0.5	1200	0.3 - 1.6
0.5	1600	0.6 - 1.4

Table 4. Trajectory Parameter Uncertainties

Parameter	Uncertainty Mach Number = 0.7 PT = 1419 psfa t = 0.75 sec
x	± 0.05
y	± 0.05
z	± 0.06
THA	± 1.40
PSI	± 0.90
PHI	± 1.21

Table 5. Grid Parameter Uncertainties

Parameter	Uncertainty	
	Mach = 0.9	
	PT = 574 psfa	PT = 1200 psfa
CN	± 0.030	± 0.006
CY	± 0.013	± 0.004
CA	± 0.011	± 0.005
CLM	± 0.012	± 0.005
CLN	± 0.007	± 0.003
CLL	± 0.001	± 0.001

Table 6. Calibration Phase Parameter Uncertainties

Parameter	Mach Number			
	0.2	0.6	1.2	1.6
$Re \times 10^{-6}$	± 0.02	± 0.02	± 0.02	± 0.02
M_i	± 0.007	± 0.003	± 0.003	± 0.004
M_a	± 0.002	± 0.001	± 0.001	± 0.001
$M_a - M_c$	± 0.004	± 0.002	± 0.002	± 0.003

**Table 7. Nominal Pressure Ratio Schedules
for CTS Testing**

M	λ^*_T	λ^*_c
0.75	1.165	1.189
0.80	1.194	1.220
0.90	1.203	1.230
1.00	1.223	1.250
1.10	1.242	1.270
1.20	1.261	1.290
1.30	1.281	1.310
1.40	1.342	1.370
1.50	1.405	1.430
1.60	1.438	1.460

NOMENCLATURE

ALPHA	Aircraft model angle of attack relative to the free-stream velocity vector, deg
CAT,CN,CY	Store measured axial-force, normal-force, and side-force coefficients, positive in the negative X_B , negative Z_B and positive Y_B directions, respectively
CLL,CLM,CLN	Store measured rolling-moment, pitching-moment, and yawing-moment coefficients, respectively; the positive vectors are coincident with the positive X_B , Y_B , and Z_B directions
M	Nominal Mach number
M_a	Free-stream Mach number calculated as the average Mach number in the calibration region
M_c	Equivalent plenum chamber Mach number
M_i	Local Mach number at an individual orifice
PHI	Angle between the store lateral (Y_B) axis and the intersection of the $Y_B - Z_B$ and $X_F - Y_F$ planes, positive clockwise looking upstream, deg
P_T	Tunnel stagnation pressure, psfa
PSI	Angle between the projection of the store longitudinal axis in the $X_F - Y_F$ plane and the X_F axis, positive when the store nose is to the right as seen by the pilot, deg
R_e	Unit Reynolds number, 1/ft
THA	Angle between the store longitudinal axis and its projection in the $X_F - Y_F$ plane, positive when the store nose is raised as seen by the pilot, deg
X,Y,Z	Separation distance of the store cg from the flight-axis system origin in the positive X_F , Y_F , and Z_F directions, respectively, ft, full scale

θ	Test section wall angle, deg (positive when walls are diverged)
λ_c	Compressor pressure ratio
λ_T	Tunnel pressure ratio, ratio of P_T to compressor inlet pressure
σ	Standard deviation

FLIGHT-AXIS SYSTEM DEFINITIONS

Coordinate Direction

X_F	Parallel to the current aircraft flight path direction, positive forward as seen by the pilot
Y_F	Perpendicular to the X_F and Z_F directions, positive to the right as seen by the pilot
Z_F	Parallel to the aircraft plane of symmetry and perpendicular to the current aircraft flight path direction, positive downward as seen by the pilot

Origin

The flight-axis system origin is coincident with the store cg at release. The origin is fixed with respect to the aircraft and thus translates along the current aircraft flight path at the free-stream velocity. The coordinate axes rotate to maintain alignment of the X_F axis with the current aircraft flight path direction.

STORE BODY-AXIS SYSTEM DEFINITIONS

Coordinate Directions

X_B	Parallel to the store longitudinal axis, positive direction is upstream at store release
Y_B	Perpendicular to X_B and Z_B directions, positive to the right looking upstream when the store is at zero yaw and roll angles

Z_B Perpendicular to the X_B direction and parallel to the aircraft plane of symmetry when the store and aircraft are at zero yaw and roll angles, positive downward as seen by the pilot when the store is at zero pitch and roll angles

Origin

The store body-axis system origin is coincident with the store cg at all times. The X_B , Y_B , and Z_B coordinate axes rotate with the store in pitch, yaw, and roll so that mass moments of inertia about the three axes are not time-varying quantities.

Superscript

• Indicates nominal pressure ratio